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NEW DATA ON COSMIC RAYS

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16. Abstract

Successes in optical, radio-wave, and ultra-short-wave astronomy have made it possible to define the diverse role which is played in the universe by high energy processes that occur in stars and nuclei of galactic star systems. Streams formed as a result of these processes of atomic nuclei and electrons accelerated to colossal energies are registered in outer space near the earth in the form of cosmic rays.

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INTRODUCTION

In 1965 the American engineers A. Penzias and R. Wilson published in the Astrophysical Journal the surprising announcement that they had discovered cosmic radio-frequency radiation which apparently fills the universe uniformly and possesses a spectrum characteristic for conditions of equilibrium with matter at a temperature of about 3° on the absolute Kelvin scale. And despite the fact that G. Gamow (also in the USA) long ago forecast the possibility for the existence of such radiation (true, he estimated the temperature not at $3^{\circ}K$, but at $5^{\circ}K$), it took several years and many new investigations to conclusively convince world scientific opinion of the correctness of Gamow's hypothesis. /3*

This hypothesis was based on the experimental fact of the expansion of the modern universe with the additional suggestion that in the distant past the universe passed through an unbelievably compressed and white-hot matter stage that was in equilibrium with a very hot and now greatly cooled down relic[1] radiation. /4

In a number of works by great Soviet and Western astrophysicists (Ya. B. Zel'dovich, V. L. Ginzburg, Ya. Oort, and others) abundant information is discussed which can be extracted from detailed observations of relic radiation, including even the possibility of measuring the speed of movement of the solar system, and our galaxy as a whole relative to the entire system of world matter surrounding us, and also estimates of the temperatures of the beginning stage of the "universal explosion" (the so-called "big bang"), which occurred more than 10 billion years ago.

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*Numbers in the margin indicate pagination in the foreign text.

1. The term "relic" emphasizes the antiquity of the origin of this radiation, its obvious nonconformity to modern astrophysical conditions.

The successes of optical, radio-wave and ultra-short-wave astronomy have made it possible to reveal the diverse role which other explosive processes of the most diverse dimensions play in the evolution of the universe. Among these processes, a sizeable place has been devoted to the study of explosions of a special class of highly unstable stars (so-called supernovae), and also to explosive processes of expansion of matter in the nuclei of galactic stellar systems - radio galaxies and large spiral galaxies of a special type. As theoretical calculations show, an enormous production of energy may take place in both cases not only in the form of the rise of shock waves in the ionized matter (plasma) moving at enormous speeds (thousands of kilometers per second), but also by acceleration of individual atomic nuclei and electrons of matter to colossal energies equivalent, in transferring to a temperature scale, to many billions and even trillions of billions of degrees. The comparatively rarefied streams of these nuclei (with an admixture of $\sim$1% of electrons) chaotically intermixed with the action of interstellar magnetic fields are registered in outer space near the earth in the form of cosmic rays.

Approximate theoretical estimates showed that, in the case of supernova stars, it would be quite possible to expend approximately 1% of the total energy of the explosion on the acceleration of particles of cosmic radiation, this energy then being sufficient for regular "pumping," maintaining an unchanged stream of cosmic rays over the course of many millions of years. Regardless of the correctness of these evaluations, direct experimental observations of the radiance of the Crab nebula pointed to the existence of intensive streams of electrons of high energy in that very area where about 900 years ago the bright flash of a supernova star was observed. A new, very /5
important experimental fact was the observation in the same spot

of a pulsar--a pulsating source of electromagnetic waves in a very broad range (up to X-rays). According to modern conceptions (still insufficiently subject to experimental data, it is true), pulsars arise during explosions of supernova stars as a result of ejecting their shells with simultaneous gravitational compression (collapse) of the remaining mass of matter of the star before reaching the state of an excaptionally dense and hot neutron star. Calculations show that the great velocity of revolution of neutron stars (this is apparent during the observation of very short and frequent bursts of radio radiation registered by ground instruments), in combination with the enormous voltage of magnetic fields ($\sim 10^{12}$ gauss) may lead to the acceleration of charged particles up to energies of $\sim 10^{18}$ and perhaps even 10^{20} electron-volts (EV). This very high-energy "tail" of the spectrum of cosmic rays is now the object of intense study by physicists for reasons which will be discussed below. Thus, already now two types of astrophysical objects in our galaxy have claims to the role of chief source of cosmic rays - the impulse, in the case of explosions of supernova stars, and the quasistationary, in the case of pulsars.

Despite the similarity of their properties in regard to very high temperatures and pressures typical for these two sources, they differ substantially in other physical and chemical conditions and, especially, in the composition of that matter out of which atomic nuclei are injected for subsequent acceleration to energies characteristic of cosmic rays.

The heightened interest displayed in recent years in the study of the nuclear composition of cosmic rays, especially in the field of heavy nuclei beginning with iron, etc., is connected with this circumstance. The reader will receive information on this question in the very first chapter of this brochure.

Returning to the phenomena of the instability of galactic nuclei, we should note that even for our "old, good" galaxy, this question is by no means useless. Although it is in no way possible to number it in the class of very violent radio galaxies or galaxies with high activity of the nuclei (the so-called Seyfert type), the processes discovered recently, which occur in a relatively small central area of the galaxy (with dimensions in the order of 10 parsecs, i.e., ~30 light years) lead astrophysicists to serious reflection. It is in no way possible to exclude the possibility that about 10 (or perhaps even 100) million years ago a gigantic explosion of the nucleus of our galaxy occurred, accompanied not only by a powerful ejection of matter, but also by the acceleration of enormous streams of charged particles. If this is so, then the presently observed cosmic rays of galactic origin are a relic phenomenon, connected with the gradual diffusion of particles from the center of the galaxy to its periphery through the "debris" of a nonhomogeneously magnetized interstellar plasma. One of the indicators of the still increasing activity of the nucleus of the galaxy in our era is the discovery during recent years of tens of superhot stars in it - powerful sources of X-ray radiation. An interesting possibility of direct discovery of the consequences of a nuclear-galactic explosion is the detailed study of the electron and nuclear composition of cosmic rays near the earth in combination with a search for possible synchrotronic "radio illumination" of cosmic electrons in magnetic fields beyond the boundaries of the galactic disk. /6

The Heaviest Nuclei and the Cosmic "Kitchen" of Chemical Elements

The extremely complex nuclear composition of primary cosmic radiation was established (by means of nuclear photoemulsions) about 25 years ago. For a long time it was considered that all nuclei except the lightest (hydrogen and helium) represent a kind of light "seasoning" for the "dishes" of the cosmic "kitchen," for their total proportion in the complete stream does not exceed 1%. But (in contrast to gastronomic problems) the question of what may be considered "seasoning" turned out to be by no means simple. /7

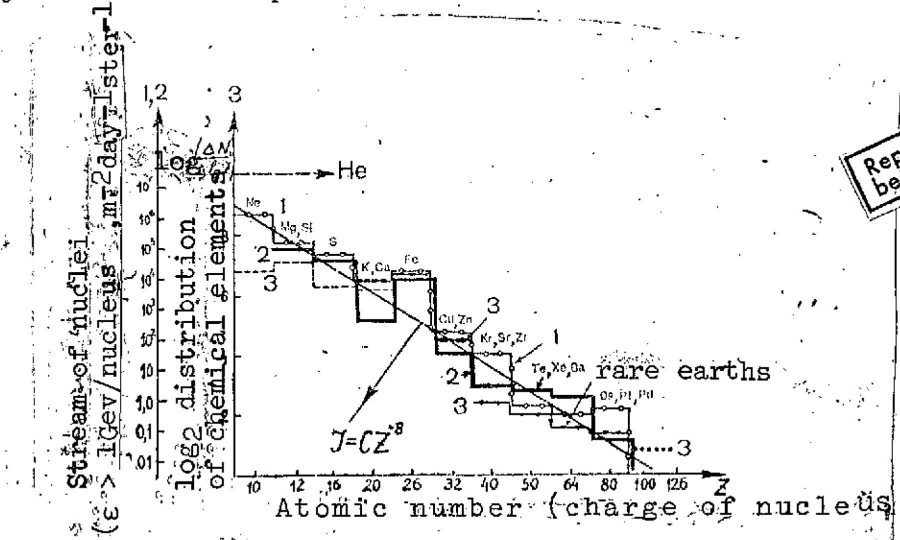

Figure 1. Relative dispersion of chemical elements on the sun (1), in the earth's core (2), and absolute streams of corresponding nuclei in the stream of cosmic radiation near the earth.

In Fig. 1 (histogram 3) a comparison is presented of modern data from various authors on the nuclear composition of cosmic rays (in a logarithm to the base two scale) and in the same place for comparison are the data collected by L. Aller in 1961 and by A. K. Lavrukhina in 1965 on the relative dispersion of chemical elements in the solar shells observed by us (histogram 1) as well as in the earth's core (histogram 2).

If one looks first only at the left half of the graph (to the left of the iron group), then it turns out that with an increase in the charge of the nucleus, the stream of cosmic

rays is enriched more and more in comparison with the representation of the same elements, let us say, in the atmosphere of the sun. The picture becomes even more convincing (cf. the Table) if we convert the nuclear composition of cosmic rays to their sources, taking into account here the fact that during their "wanderings" in the interstellar medium the nuclei of /8
cosmic rays sometimes meet with the nuclei of interstellar hydrogen and "collapse" into lighter "fragments." It is this very process which explains, in particular, the presence in cosmic rays of a noticeable admixture of very light nuclei of Li, Be, and B, the number of which is insignificantly small in the atmosphere of the sun (and the solar system in general).

Let us turn now to the right part of Fig. 1. By analyzing

THE NUCLEAR COMPOSITION OF COSMIC RAYS, CONVERTED TO THE SOURCES (THE NUMBER OF NUCLEI OF CARBON IS TAKEN AS EQUAL TO 100).
Data of M. Shapiro, R. Zilbergerg, and S. Tsao (USA)

Distributed elements	H	He	C	N	O	Ne	Mg	Si	Fe
	$2 \div 5^{*} \times 10^{4}$	$2{,}7 \times 10^{3}$	100	12	102	20	27	23	23
Rare elements	Na	Al	S	Ar	Ca	Ni			
	1	1	4	2	2	1			
Very rare elements	$Z = 29 \div 43$ (Se, Kr etc.)	$Z = 44 \div 56$ (Te, Xe etc.)	$Z = 57 \div 83$ (Pt, Os, Pb etc.)	$Z = 90 \div 96$ (U, Np etc.)					
	0,1	0,0003	0,0003	0,0002					

Estimates are connected with the suggestion as to whether the acceleration of nuclei in the sources is determined by their energy or by the so-called hardness $R = Zp$, where p is the impulse.

it at least three important conclusions may be drawn. First of all, immediately after the iron group there occurs a sharp fall in the dispersion of elements (by a magnitude on the order of 2 - 3). This peculiarity is very skillfully used now in experimental investigations for calibration of detectors of multicharged particles according to the nuclei of the iron group, the very abundance of which will serve as an excellent "visiting card" for them. In regard to the astrophysical reasons for the special role of the nuclei of iron, it may only be guessed that they are somehow connected with the maximally compact "packing" of the component parts of this nucleus - the nuclons. This compactness is revealed in a maximum amount of the defect of the mass, i.e., the specific (in calculating for one nuclon) energy of the bond and the corresponding (in accordance with the theory of relativity) decrease in the average mass of the nuclon bound in the nucleus in comparison with a free one. Therefore, it may be surmised that, externally also, the shells of the densest stars - the neutron stars - consist almost completely of iron. We note that it is precisely the neutron stars which are now considered the most probable candidates for the role of a constantly operating "generator" of cosmic rays.

The second conclusion from the diagram of Fig. 1 is that the distribution of all nuclei heavier than iron both in cosmic rays and in substances of the solar system quickly diminishes with an increase in the charge of the nucleus Z and the atomic element approximately according to one and the same law $J(Z) = CZ^{-8}$. This circumstance makes life extremely difficult for the experimenters, demanding that they have apparatus with enormous area or very long time limits of exposure for this apparatus. Thus, for example, in order to reach the group Os - Pt - Pb ($Z > 70$), it is necessary to register streams of particles in the order of 1 in 1 m^2 every 24 hours (or cor- /10 respondingly in the order of 1 in 300 cm^2 per month), even in a case when one succeeds in registering and measuring nuclei falling at any angles.

Finally, the third, and, doubtless, the conclusion which most excites the minds of scientists now, is that in cosmic rays, indications are obtained (true, as yet too few in number and not completely reliable) of the existence of nuclei which are heavier than uranium. It is even possible that among the two events, publicized by the Anglo-American group of scientists in 1971, at least one is connected with the passage through the apparatus of a nucleus which is heavier than curium (Z = 96). If this observation is confirmed by further experiments, then cosmic rays will turn out to be a powerful rival of modern accelerators, in which physicists (in Dubna, USSR, and in Berkeley, USA) will succeed now in obtaining elements right up to No. 105.

At first glance such a possibility seemed practically completely excluded, inasmuch as with the increase in atomic number of transuranic ($Z > 92$) elements, their lifetime decreases catastrophically, measuring, let us say, tens of seconds for element No. 105. But theoretical studies of recent years show that when $Z > 105$ apparently an increase in lifetime must set in again, connected with the special role of stable (closed) nuclear shells, which consist, probably, of 114 protons and 184 neutrons. Despite the great indefiniteness in these calculations, the existence of an "island" of almost stable transuranic elements, possessing at times a life of about 1 million years and more, is now not doubted by theoreticians.

In discussing the possible methods of reaching this sacred "island," two sharply different methods are presented. One of them, suitable only for special astrophysical objects with gigantic temperatures (billions of degrees) of the surface, consists of consistent capture of neutrons, occurring every few seconds. This so-called r-process (from the English word "rapid") has been achieved only to a mild degree in thermonuclear explosions on the earth (thus American physicists produced elements No. 99 and 100).

Another method, much more convenient for laboratory investigations, consists in bombarding the heaviest, sufficiently stable elements (uranium, plutonium, americium) with possibly heavier ions speeded up in accelerators to energies of hundreds of millions of electron-volts. Up to this time, it is true, such attempts did not allow the further advancement of the short-lived element No. 105 (it was suggested that it be named Nilsbohrium), but further, more and more heroic efforts in this direction are continuing. /11

Returning again to Fig. 1, we see that hope for success in work with cosmic rays will occur only in the event that scientists succeed in realizing in an experiment in outer space a trial with a light force in the order of 10 m^2 per month. For this purpose it would be possible to use orbital space stations.

Electrons - an Important Component of Cosmic Radiation

The problem of the nature and origin of cosmic rays has its own long and complex history. At one time it was thought that they are gamma-quanta, arising in the processes of mass annihilation of antimatter. Then, when the great influence of terrestrial magnetism on the stream of primary radiation was discovered, researchers began to turn toward electrons. And only after that did the correct solution to the riddle come in the form of proton-nuclear composition.

A significant improvement in instruments and in the entire method of measurement was necessary in order to again "rehabilitate" electrons to some extent, to prove that they too are present in primary cosmic radiation. According to the accidental coincidence of circumstances, their proportion in the total stream turned out to be about 1% - approximately the same as the proportion of all nuclei which are heavier than helium. At the beginning it was thought that such a small admixture affords no interest, for it could be formed also as a secondary product of the interaction of protons and nuclei with interstellar matter. But then from observations and detailed calculations it became clear that such a "trivial" explanation does not suffice at all - interstellar matter can ensure only a small proportion of this percentage (Fig. 2), and too few of the expected positrons are observed together with electrons in the experiment. /12

On the other hand, upon reflection the physicists understood that with equal conditions of acceleration of the charged particles in the stream of primary radiation, in no way may an equal number of electrons and protons be obtained. There are at least two reasons for this: the electrons, as very light particles, must experience great additional losses of energy, in the first place, to braking (so-called synchrotonous) radiation [Bremsstrahlung] of γ-quanta in magnetic fields, and in the second place, in collisions with photons of the electromagnetic field (the so-called reverse Compton effect). The Soviet astrophysicists V. L. Ginzburg and I. S. Shklovskii were first to suggest that this obvious shortcoming of electrons be turned to an important advantage. Actually, the collisions of photons with electrons should take place where there are many electrons, and besides, where the magnetic fields are large, i.e., where intensive acceleration of cosmic rays occurs. The γ-quanta themselves no longer are deflected in magnetic fields on the way to the observer. Thus, the opportunity is presented for direct experimental observation of the sources of cosmic rays in the universe!

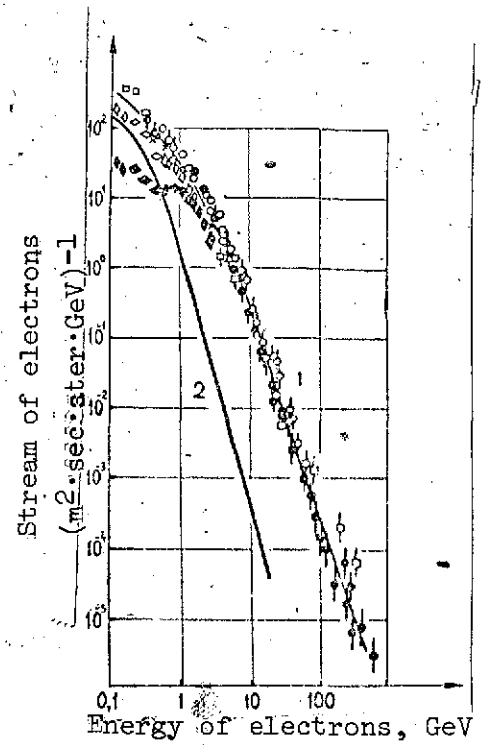

Fig. 2. Energy distribution of primary electrons (1) and the expected spectrum of secondary electrons (2) according to calculation.

The first serious success came as early as 1956 when radioastronomers "took aim at" the Crab nebula, which arose about 900 years ago as a result of the explosion of a supernova star. /13

Since then the Crab nebula has become certainly the most popular object of astrophysical observations in the widest range of wavelengths - from radio waves to quanta with energies in the order of 10^{12} eV, which constitutes almost 20 (!) orders of magnitude. In these observations it was reliably established that the Crab (as astrophysicists familiarly call it) is saturated with powerful streams of electrons with energies from 10^8 to 10^{14} eV, and that all of them circulate in magnetic fields which are small compared to those of the earth (10^{-4} - 10^{-3} gc), but which are at the same time very extensive. For electrons with energy of more than 10^{10} - 10^{11} eV the magnetic Bremsstrahlung in these fields will become so strong that they are practically unable to maintain any noticeable (according to astronomical scales) time without substantial "pumping."

Success also occurred in discovering the source (at least one) of this pumping - a pulsar with the code designation NP0532, which "works" at capacities of $\sim 10^{38}$ erg per second, i.e., which is much more active than our sun, which radiates primarily in an optical range.

It is interesting to note that an earthly observer perceives the pulsating (like a beacon) regime of action of the pulsar NP0532 to an equal degree both in the optical and in the X-ray range of wavelengths. This may mean that not only streams of plasma, but also clusters of greatly accelerated electrons "erupt" with this pulsar in the narrowly directed manner. The direction of the radiation in combination with the swift rotation also ensures the effect of the "beacon of the universe".

By lifting sensitive apparatus on stratostats - vertically propelled rockets - and then on earth satellites, scientists succeeded in avoiding the "barrier" in the form of the earth's atmosphere which previously hindered them. In recent years it has been X-ray astronomy which has made a triumphant advance; it has become the object of mass attraction of specialists not only on galactic, but also on extragalactic objects. Tens of X-ray stars have been discovered in the nucleus of our galaxy, many disputed and sometimes indisputed sources also in those places where, previously, the most powerful compact sources of radio wave (radiogalaxies) and optical (quasars) radiation were discovered. /14

Observational data on discrete X-ray sources are quite varied and sometimes little understood. The forms of their energy spectra differ from case to case, with a greater or lesser degree of amplitude and regularity, the very intensity of illumination changing, and it is not always possible to eliminate background phenomena by correction.

Nevertheless more and more that special role becomes clear which is played by electrons accelerated to relativistic (near-light) speeds and streams of red-hot plasma, carrying with them a magnetic field in the most varied sectors of the universe marked by very violent, quite unstable processes occurring with the production of enormous amounts of energy.

Thus, for example, in the nucleus of the galaxy with the nomenclature designation NGC1275 at a distance of ~200 million light years from us, already several million years ago the throwing off of clouds of plasma with a total mass of about 100 million masses of our sun and at speeds at present of ~3000 km/sec began, and this has continued up to the present day.

In radio galaxy M87 a stream of particles shining with synchrotronous illumination has been thrown off already to a distance of ~5000 light years.

In the most distant objects - quasars - the energy produced with synchrotronous radiation of electrons would correspond to the complete annihilation of antimatter in the amount of 10 - 100 million masses of the sun.

From many spiral galaxies there occurs a throwing off at great speed of clouds of plasma with masses of many thousands of masses of the sun. There are also indications that, comparatively recently, according to cosmological standards (probably about 10 million years ago), the last intensive ejection of huge masses of gas from the nucleus of our galaxy also began. And the very character of the spiral structure of the galaxy may be connected with a similar process.

A detailed study of the energy spectrum of the electronic component of cosmic rays in combination with such careful measurements of the spectrum of radio radiation coming from various sections of the galaxy can, in principle, outline the spatial /15 boundaries of that region (halo or aureola) which is filled with swift-moving electrons from all galactic sources. In particular, calculations made in 1971 by S. I. Syrovatskii and his associates showed that the observable aspect of the electron spectrum corresponds best to the idea of a thickness of the galactic "aureola" of 1000 parsec, which exceeds by approximately ten times the thickness of the disk filled with all the stars of the galaxy.

Thus, the electron component of cosmic rays, taking into account the radio signals of magnetic Bremsstrahlung that it yields, turns out to be a peculiar instrument for defining the structure of the galaxy, including indirectly its invisible part, filled with the "exhaust gases" of cosmic plasma.

How Old Are Cosmic Rays?

In the course of the 60 years which have passed since the time when the experiments of the Austrian physicist V. Hess established the actual extraterrestrial character of cosmic rays (and thus this very term acquired the "rights of citizenship"), the secret of their origin has not ceased to interest scientists. As was noted in the previous section, radio astronomical observations permitted the perception of those "hot points" in our galaxy where the electron, and probably also the nuclear component of cosmic radiation arises. We are speaking here of the exploding supernova stars and their descendants - pulsars - which are, according to modern ideas, unbelievably hot and superdense neutron stars.

By astrophysical standards our entire galaxy is only a modest little island in the universe that light and radio waves have passed "through and through" over a period of "some" 100,000 years. The speed of the charged particles does not practically differ from the speed of light, but nevertheless they are doomed to much longer wanderings in the galaxy[1]. The reason for this /16 is the distorting action of interstellar magnetic fields, which are insignificantly weak (on the average about one million times weaker than near the earth), but which nevertheless possess an enormous extent and a complex, nonhomogeneous structure. The movement of cosmic particles in these fields has an unbelievably confused, chaotic character, and may be compared completely justifiably with the diffusion of molecules of a gas, the speed of which under normal conditions is hundreds of times lower than the speed of movement of the molecules themselves.

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1. One must keep in mind the fact that at least a small portion of cosmic rays with the highest energies can also have an extragalactic origin.

Through detailed study of the nuclear composition of cosmic rays, physicists 10-15 years ago already knew rather accurately how much matter must "penetrate" them on their path. According to terrestrial standards this is very little, a total of 3 - 5 g in a column with a dimension of 1 cm^2, i.e., 200-300 times smaller than in passage through the earth's atmosphere. A layer of interstellar matter of just such thickness (chiefly hydrogen) leads to the fact that about 1/4% of all cosmic nuclei consists of the elements Li, Be, and B, accumulated in the process of fragmentation (disintegration) of all the other, heavier nuclei.[1]

But, to be sure, for a determination of the duration of wanderings of cosmic rays in the galaxy neither knowledge of their speed nor knowledge of the total layer of matter penetrated is sufficient. It is necessary to know in addition the density of the matter, and not simply for the disk of the galaxy "populated" by stars, but for the whole of the area visited by its magnetic fields, that is, the trajectory of cosmic particles. Even ten years ago it was thought that our galaxy, as many other star systems which are visible to us from the side, possessed an almost spherical halo - a so-called area filled with a magnetic field and streams of fast electrons "shining" (in a radio range) in these fields.

But careful studies of the frequency spectrum and the angular anisotropia of radio radiation of our galaxy in combination with data on the energy spectrum of cosmic electrons, forced some specialists, in particular S. I. Syrovatskii (P. N. Lebedev Physics Institute of the USSR Academy of Sciences), to substantially revise their views on this whole problem. It turned out that a lentil-shaped rather than a spherical halo, only /17

1. Here it is considered that the contents of Li, Be, and B in matter from any possible sources of cosmic rays is insignificantly small.

10-20 times thicker than the basic disk of the galaxy, filled with stars, corresponds much better to observations.

This "revision" immediately requires a corresponding revision of estimates of the average density of the medium penetrated by cosmic rays - up to 1 atom of hydrogen per 1 cm^3 instead of 0.1 atom, as it would be in the case of a spherical halo.

But from this follows the "rejuvenation" by a factor of ten of cosmic rays themselves - to 10 - 30 million years instead of the previous estimate of 100-300 million years. The "rejuvenation" of cosmic rays finds support also in at least two types of modern data on their composition. In the first place this includes data on the relative number of nuclei of Be in comparison with the nuclei of Li and B. One of the isotopes of beryllium - Be^{10} - disintegrates very fast (according to astronomical standards), on the average over a period of 2.5 million years. The data known from terrestrial experiments (in accelerators) on the fragmentation of the heavier nuclei show that taking into account the radioactive isotope Be^{10}, the ratio of Be/(Li + B) must be 0.41, and without this isotope - 0.27 in all. Since on experiment the ratio Be/(Li + B) is obtained significantly nearer to the first magnitude, it must be concluded that Be^{10} hardly succeeds in decaying. Therefore, the estimate of 100 (and even 50) million years for the age of cosmic rays is obviously increased.

In the second place, there are indications, so far not very reliable, of the presence of transuranic elements in cosmic rays. Inasmuch as in nature there do not exist (more exactly, they are so far unknown) transuranics with a "long life" of tens of millions of years, one must nevertheless lean to the concept of the relative "youth" of cosmic rays.

The totality of modern data leads to a truer estimate of the age of cosmic rays of 10-20 million years.

The Starlit Sky in Gamma Rays

Who is not acquainted with the picture of a clear, starry sky on a cloudless and moonless night far from the city, especially high in the mountains where the atmosphere is more transparent than the best glass? But if our eyes succeeded even for a minute in "switching over" to another range of radiation, in a field of approximately three times shorter waves, then immediately this transparent "glass" would be transformed into impenetrable blinds, completely hiding from us the sun, the moon and the stars. /18

It is therefore not surprising that with the beginning of the space era, with a passage beyond the boundaries of the earth's atmosphere, mankind received a very unique opportunity to look into the world surrounding us in a completely new light. Of course, this very unusual "glance" also required completely new, artificial "eyes," the action of which was based no longer on biochemical, but on strictly physical, processes. True, two eyes are not required here (you do not in any case achieve a stereoscopic effect), but this eye must be opened very wide. The reason for this is simple: If you are oriented for a typical area for cosmic rays of energies in hundreds of Mev, then you must take into account the fact that, although every quantum of radiation carries with it hundreds of millions of times greater energy than the optical quantum of visible light, the very stream of such quanta is insignificantly weak - it is calculated in units per square meter per square second (Fig. 3).

In 1968 the American physicists G. Clark, G. Garmire, and W. Kraushaar published in the Astrophysical Journal the first, still rather scanty astronomical observations. But after this came an ever-growing avalanche of other observations, including Soviet ones, conducted on satellites of the "Cosmos" series.

First of all, these observations established that the zone of the Milky Way, i.e., the "heavenly track" of our galactic star system, is emitted into the firmament barely less brightly than are the visible rays. In this case, however, it turned out (Fig. 4) that in contrast to the optical Milky Way, the gamma-luminescence /19 of our galaxy is very uneven. If one calculates the galactic length from the direction to the center of the galaxy, then in the longitudes 90° and 270° the total "luminescence" decreases approximately by a factor of 5. In rough approximation it may be considered (Fig. 4) that this luminescence is proportional to the square of the total amount of interstellar material (basically hydrogen) intersected by a ray of sight.

It is interesting that approximately the same picture of the Milky Way is obtained in X beams also, if one travels in a meridional direction (Fig. 5a), but only in a case when not very "soft" radiation is discussed, with an energy of quanta of more than 1 keV. When, however, very soft radiation is produced (E = 0.2 — 0.5 keV), then the surface of the galaxy "shines" no brighter than its poles (Fig. 5b), and, therefore, individual X-ray stars are produced against the general background very clearly.

The approximate proportion of gamma and x-ray radiation of the galaxy to the square of the amount of interstellar gas led the Japanese physicists S. Hayakawa and I. Tanaka to suggest that all these high-energy quanta are connected with early stages of the development of young (according to astrophysical standards) stars, and, in particular, with remnants of exploding supernova stars.

Actually, by methods of radio astronomy in the galaxy already about 600 "remnants" of supernovae, or more exactly, of swiftly expanding shells cast off by them, have been discovered. A rather successful attempt was even made to follow /20 the correlation by galactic longitudes between streams of γ-radiation and that "radio luminescence" which can be ascribed to magnetic Bremsstrahlung of swift cosmic electrons in magnetic fields of expanding shells of supernovae.

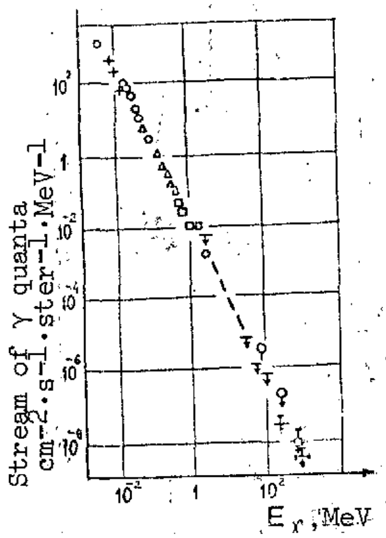

Fig. 3. Energy spectrum of γ-quanta according to data of various authors (the arrows indicate the results, giving only the upper boundary of the possible stream).

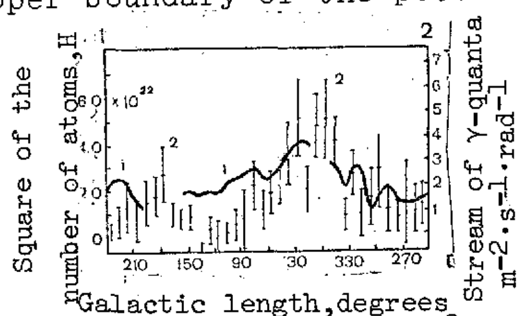

Fig. 4. Dependence of a stream of galactic γ-quanta on galactic longitude. The data on the square of the number of hydrogen atoms of interstellar matter (according to beam of vision) are plotted in a continuous line.

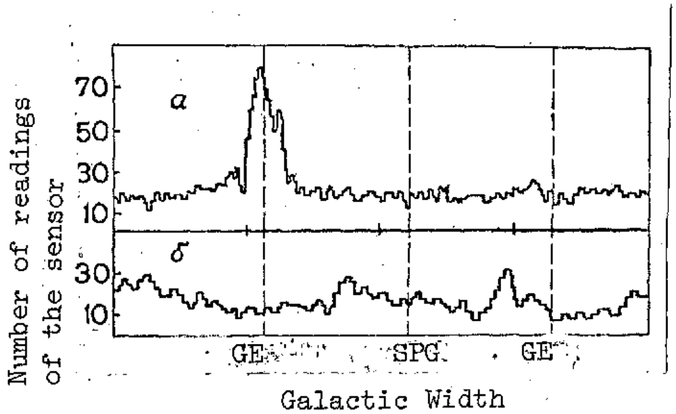

Fig. 5. Distribution of streams of X-rays from the galaxy in a meridional plane:
a - for quanta with energy >1 keV; b - for quanta with energy of 0.2 - 0.5 keV. GE - galactic equator. SPG - southern pole of the galaxy.

An although the hypothesis of the Japanese scientists cannot as yet be considered proven, it will become clear why the average intensity of galactic γ-radiation is much higher than the amount which was expected earlier in the proposition that cosmic rays equally fill the whole galaxy and create γ-radiation through an intermediate stage of formation of π^o-mesons in the nuclei of interstellar matter. By the way, in order to speak seriously /21 in general about the role of π^o-mesons, it is necessary still, as V. L. Ginzburg has noted, to study in detail the energy spectrum of the quanta themselves, which, in the case of the π^o meson process must have a typical maximum of nearly half the energy of rest of a π^o-meson, i.e., 70 MeV.

Now a number of X-ray sources have already been reliably discovered also among extragalactic objects, not speaking of the many exceptionally bright extragalactic sources of light-- quasars-- and sources of radio radiation - radio galaxies. Therefore, the search for extragalactic sources is of great interest. In 1971 a group of scientists from the Scientific-Research Institute of Atomic Physics of Moscow State University (A. S. Melioranskiy and others), who conducted their investigations on the satellite "Kosmos - 208", published the results of the search for γ-quanta from 11 of the brightest extragalactic objects, including the quasar 3C273.

Unfortunately, these types of observations are insufficiently sensitive (because of the enormous remoteness of the γ-sources) and they gave only the upper limits of streams on the level of several quanta in the calculation for 1 m^2 of the γ- telescope during 1 second.

More perfected apparatus (with the use of spark chambers) was developed by a group of physicists from the Moscow Engineering-Physics Institute (A. M. Gal'per and others), which made their observations on the satellites Kosmos-251, Kosmos-264, and Kosmos-280. This group for the first time succeeded in discovering a noticeable excess over the total γ-background in the region of the constellation Taurus, 30^0 from the galactic surface, which they ascribed to the special source "$\tau\gamma^{-1}$".

The authors suggested that this source coincides with the well-known radio galaxy ZS120 which is variable in intensity. But in such a case the conclusion followed that the power of this galaxy in the γ-range is on the order of 2 - 3 magnitudes greater than in optical and radio ranges, constituting $\sim 10^{47}$ erg/sec. If this identification proves true, then the ZS120 galaxy must be called a gamma-galaxy. The data of Gal'per and his colleagues were later confirmed by foreign scientists.

Our Restless Sun

In the first stages of the study of cosmic rays it was thought that their sources could be sought anywhere except on the sun. It seemed that this was indisputable because the stream of cosmic rays is practically independent of time of day. /22

This opinion wavered somewhat on 28 February 1942, when a suddenly increasing stream of cosmic radiation at sea level reacted on a powerful and rather prolonged (over the course of 3.5 hours) local increase in brightness of the solar disk - a so-called chromospheric flare of the hydrogen line H with an almost simultaneous cessation of short-wave radio communications. Similarly, parallel phenomena were repeated again in 1946 and 1949. Indirect estimates showed that the particles of exceess cosmic radiation should possess energies of up to 10 GeV.

Following soon after this recorded burst of cosmic rays on 23 February 1956, when the neutron component already jumped 50 times over the noral level, the International Geophysical Year was announced (IGY). The worldwide network of stations for constant ground registration of cosmic rays created at this time was supplemented by regular high-altitude observations on balloons, geophysical rockets, and then artificial earth satellites.

The high-altitude observations allowed a sharp reduction in requirements for energy of the cosmic protons registered--to approximately 100 MeV. And the fact that the year 1958 was expected to be a year of maximum solar activity, including maximum frequency appearance of sunspots and chromospheric flares, played an important role in the composition of the program for the International Geophysical Year. The results of this international activity proved to be sufficiently abundant - in every month of 1958 a more or less simple coincidence (correlation) between a chromospheric flare on the sun and the burst of a stream of cosmic rays - apparently protons and α-particles - occurred from one to three times. In the same year for the first time /23
still another accompanying phenomenon was successfully observed - a short-duration (lasting 18 seconds) flare of X-ray radiation from the sun. This new phenomenon, similar to the switching on

of an X-ray machine, gradually led the scientists to the idea of paying special attention to the search for electron streams in interplanetary space - even if at much more modest energies - tens of kiloelectron-volts "in all".

Such observations first met with success in 1960, during the flight of the space vehicle Pioneer-5. Much broader information was obtained by the American scientists K. Anderson and R. Lin as early as 1964-1965 with the aid of the satellites IMP-1 and IMP-3. They showed that in 7 cases out of 10 one could point out those relatively small (1 on the scale) chromospheric flares, after which followed (wtih a delay of 30-40 min) bursts of electron streams with energies of more than 40 keV. And here the important advantages of the observations of electrons were made clear: they make it possible not only to follow the direct genetic connection between the acceleration of swift, charged particles on the sun, but also to make a much more reliable "connection" in time, and even in space. Actually, the slow protons (an excess of which was observed on "Pioneer-5"), spend approximately 10 times more time on the "journey" from the sun to the earth, and the entire situation on the sun succeeds in changing noticeably. Besides, the trajectories of movement of the electrons themselves are much less subject to the influence of chaotic processes such as diffusion through clouds of magnetized plasma - especially in the initial stage of the whole process. Detailed comparisons with the solar coordinates of chromospheric flares showed that in a significant proportion of cases, electrons are thrown off from the sun in a comparatively narrow, cone-shaped stream, spirally curved in accordance with the force lines of the magnetic field.

Investigations over many years, chiefly by scientists of the USSR and the USA, permitted the establishment of the following classification of chromospheric flares on the sun.

Type 1. Heat flares

They occur almost constantly - up to 10,000 times in a year of maximum solar activity, but they are nevertheless small in area and weak in brightness, and are accompanied by comparatively slow local heating of solar plasma by electrons up to temperatures of tens of millions of degrees. In addition, soft X-ray and radio-wave electromagnetic radiation is released (changing just as slowly). /24

Type II. Electron flares

They may appear on the average almost every day (~300 times in a year of maximum activity) and they also occupy a small area, but at the same time are characterized by a sharp burst of brightness in the line H_α, and at the same time also in the field of hard X-ray (tens of keV to a quant) and in the ultraviolet field. In case of a favorable magnetic "situation" (interrupted force lines), intensive streams of electrons with energies of 10 - 100 keV explode with this into the sun's corona, producing in it microwave radiation and following on into interplanetary space to the orbit of the earth and 100 - 200 million km beyond it. The spatial scheme of the phenomena occurring with this is shown in Fig. 6, and their temporal order in Fig. 7.

Type III. Proton flares

These are more powerful, but at the same time, rare phenomena (~30 cases in a year of maximum activity), embracing large areas of the solar disk. They are accompanied by an emission of electrons with energies of up to 30 MeV, and also of protons and complex nuclei, usually with energies of up to 100 MeV (to a nuclon). Together with this, multiple flares of hard X-rays and a wide range of short-wave and radio-frequency radiations are observed.

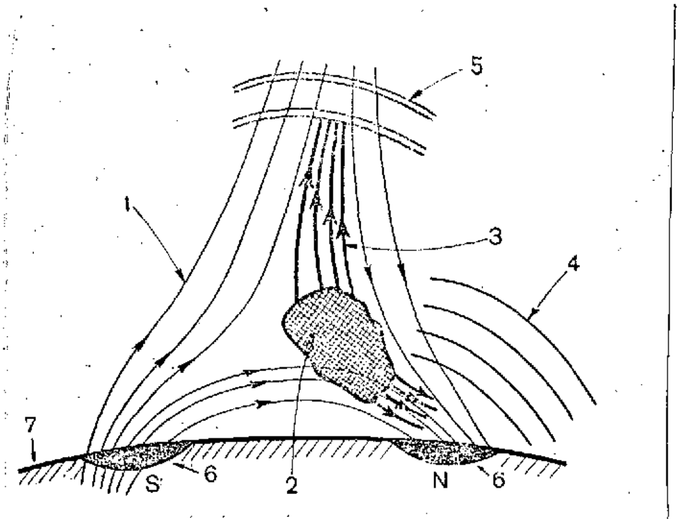

Fig. 6. Spatial picture of physical phenomena during solar flares: 1--magnetic force lines: 2--field of acceleration of electrons; 3--emission of electrons into the interplanetary medium; 4--X-ray, ultraviolet, and microwave radiation; 5--type II radio radiation; 6--sun spots; 7--boundary of the photosphere of the sun.

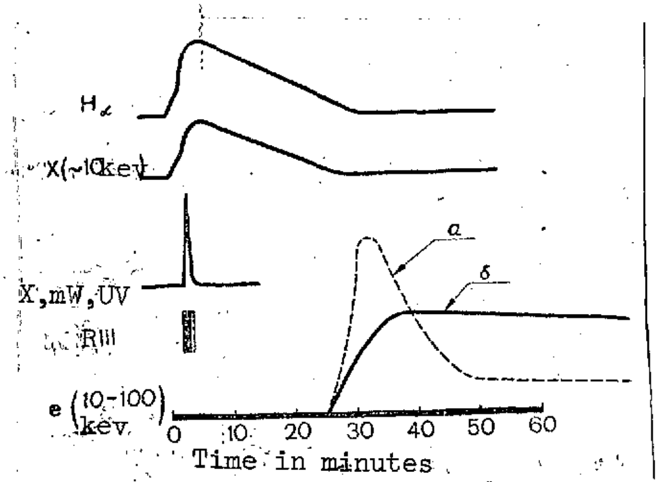

Fig. 7. Temporal sequence of phenomena during solar flares: the H_α-intensity of the hydrogen line α, X(~10 keV) --soft X-ray radiation; X, mW, UV--hard X-ray, microwave, and ultraviolet radiation, RIII--type III radio showers, e (10-100 keV) - streams of electrons near the earth with free (a) and diffused (b) distribution.

There is as yet no single theoretical solution to the problem of the rise of the whole gamut of solar flares. The hypothesis of S. I. Syrovatskiy receives the greatest credence in scientific circles (and not only in the USSR). He proposed a model connected with the rise and disintegration of current layers in the field of annihilation (or zero points) of magnetic fields. In application to chromospheric flares, this model in simplified form may be presented in Fig. 8, which gives a vertical section of the sector of the photosphere containing two sunspots of opposite polarity. With suitable orientation of the magnetic moment of the spots $\vec{M}$ (it is necessary that they be parallel to the external field $\vec{N}$) in the impact of points of the oppositely directed force lines, there arises a semicircular line of the zero field directed perpendicular to the plane of the sketch. With a movement of the spots (Fig. 8b) or a change in their magnetic field on the zero magnetic line there arises an electrical field and with it also a current layer in which there occurs acceleration of electrons to energies of tens and even hundreds of kiloelectron-volts.

/26 /27

As an analysis of the observations shows, the total number of electrons accelerated when there are bright flares on the sun constitutes 10^{35} - 10^{36} particles. The energy included in them (10^{27} - 10^{28} erg) constitutes about 30% of the complete energy of the flare, and although only proportions of a percentage of this amount "slip away" with electron streams into interplanetary space, even this exceeds by millions of times the effect of the explosion of the most powerful hydrogen bombs.

Records of Superhigh Energies and the Problem of Metagalactic Sources

Every natural source of particles or radiations has its own typical energy spectrum. Linear in the case of α - or γ -

radiation; constant in the case of β particles, these spectra together with the lifetimes of their sources, are a kind of "passport" characteristic of various radioactive elements. And primary cosmic radiation, which fills our galaxy, has its own characteristic energy spectrum. With energies of tens of billions of electron-volts and higher, galactic radiation has not yet been "soiled" by cosmic rays of solar origin, and it has not been subjected to the influence of the magnetic field of the earth.

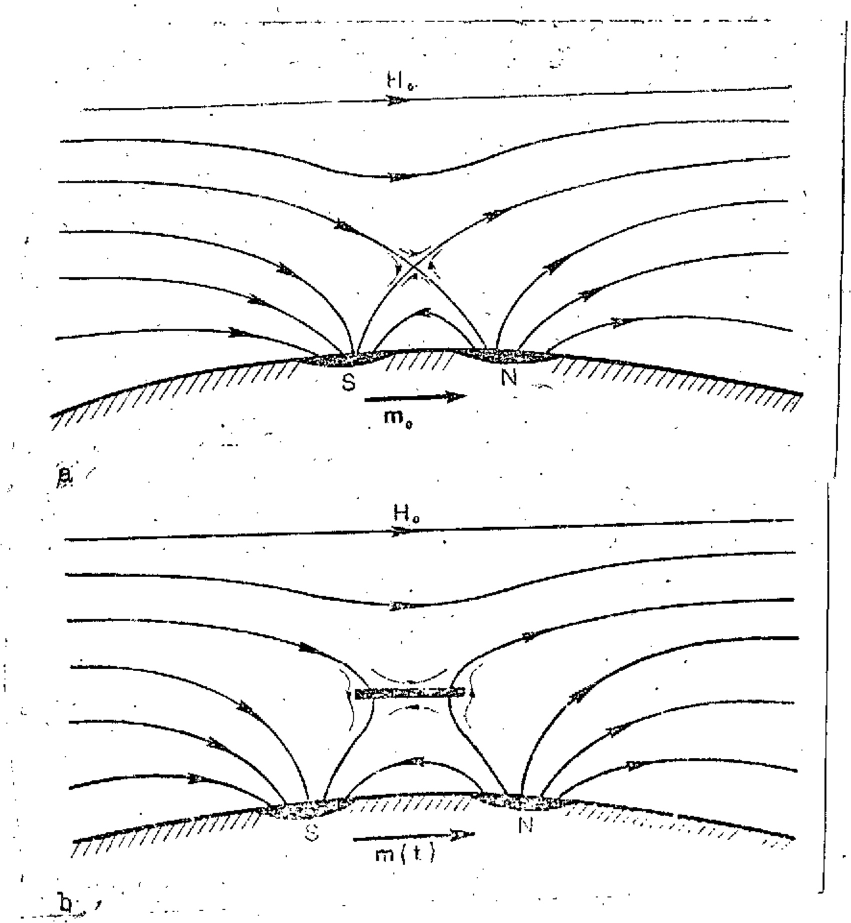

Fig. 8. Rise (a) and development (b) of the current layer over a bipolar group of sunspots: m - magnetic moment of spots of opposite polarity.

The group of N. L. Grigorov from Moscow University, which used for this purpose apparatus set up on four artificial earth satellites of the Proton series in 1965-1968, advanced farthest of all in direct measurements of the energy spectrum beyond /28 the bounds of the earth's atmosphere. The basis of this apparatus was the ionization calorimeter. It consists of many rows of scintillating measuring devices, stratified with iron filters, which allows one to follow the gradual absorption of all products of nuclear interaction of the cosmic particle and to determine the total energy produced in such a process.

As is apparent from Fig. 9, the experimental data obtained on the Protons extend even to energies of approximately (2 - 3) x 10^{15} eV. The total stream of paritcles with energy higher than 10^{15} consitutes, according to these figures, about 10^{-6} in 1 m^2 in 1 sec. in calculation for a body angle of 1 steradian (the real "angle of vision") of the apparatus constituted a total of ~ 0.1 steradian.

With the further increase in energy, this stream swiftly decreases, approximately as $E^{-1.7}$ (i.e., 50 times for every order of magnitude of energy). It is not difficult to calculate that even bringing the area of the instrument up to 10 m^2 (its weight should thereby be about 100 t), with the same transconductance of the energy spectrum, it would be necessary to continue measurements on the satellite for about 100 years in order to "catch" even one cosmic particle with energy of 10^{17} eV. The solution of such a problem "head-on" clearly transfers to the field of utopia.

Fortunately, specialists learned a long time ago to use as a peculiar calorimeter no more nor less than the thickness of the earth's atmosphere. The fact is that any primary cosmic

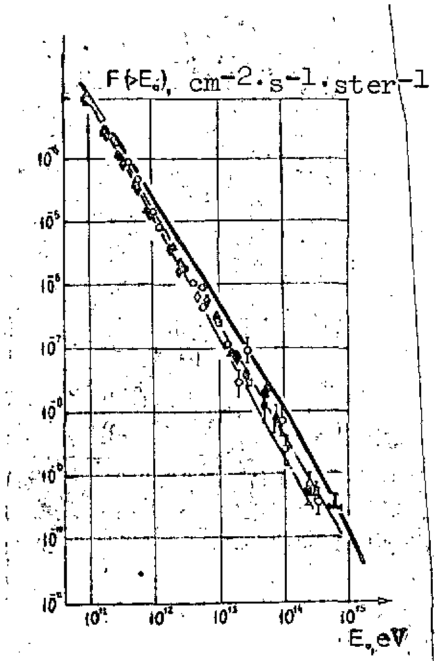

Fig. 9. Integral energy spectrum of primary cosmic radiation according to data from satellites of the Proton series.

particle with energy of $> 10^{14}$ eV already in the very upper layers of the atmosphere (at altitudes of about 20 km) must collide with one of the nuclei of the atoms of air. With this an avalanche of /29 consecutive nuclear interactions of newer and newer generations of particles - nuclons and mesons - is engendered. Among the various secondary particles π-mesons - there arise neutral mesons (π^0), which begin the swiftly branching "chain" reaction of processes of the type $\pi^0 \rightarrow 2\gamma$ (disintegration into 2 γ-quanta), $\gamma \rightarrow e^- + e^+$ (birth of electron-positron pairs), and finally, $e^{\pm} \rightarrow e^{\pm} + \gamma$ (Bremsstrahlung of γ-quanta by positrons and electrons).

The ever increasing angles of dispersion of positrons and electrons when they collide with the atoms of the air leads to the development of a very broad avalanche of particles "irrigating" the area, calculated as a function of the energy of the initial particle in one or even many square kilometers. It is sufficient to place on the surface of the earth a suitable system of detectors of charged particles in order to determine the total number of electrons in such avalanches, which have received the name of broad atmospheric showers (abbreviation - BAS). If one learns, furthermore, the average energy spectrum of electrons, averaged for distances from the axis of the shower, that is, also their average energy (it is in the order of 10^9 eV) and introduces a rather well-known correction for the energy of the remaining particles of the shower (photons, neutrinos, μ-mesons), it is also possible to transfer from the total number of electrons in the shower to an estimate of the sought-after energy of the primary particle.

Devices for the registration and multifaceted investigation of broad atmospheric showers were built in a number of countries - the USSR, the USA, England, Japan, France, Poland, and even in far-off Australia. Among the results obtained by them, we would like to mention first of all the peculiar behavior of the primary energy spectrum in a range of energies of 10^{15} - 10^{17} eV. As is evident from Fig. 10, the slope of the spectrum here undergoes two breaks: at the beginning it becomes steeper, and then, apparently, it is restored to the previous amount of 1.7 (when the spectrum is depicted in a logarithm to base two scale).

As was noted for the first time by G. B. Khristiansen from Moscow University, such a behavior of the spectrum can mean that with energies in the order of 10^{17} eV the possibilities of intragalactic processes of acceleration and detension of particles are /30 exhausted, and large-scale-metagalactic processes enter into play.

No less important for the theory of the origin of cosmic rays is the question of the energy capabilities of the metagalaxy. As was shown by G. T. Zatspein (Physics Institute of the Academy of Sciences, Moscow), despite the exceptional rarefication of the intergalactic medium, it proves to be a serious hindrance for the dispersion of particles in it (in particular, protons) with energies of $3 \cdot 10^{19}$ eV and above. It is interesting that the chief source of losses of energy are collisions, not with matter, but with radiation - with quanta of relic radiation that fills the universe.

In order to experimentally clarify the situation, it was necessary to build a device with an area of many square kilometers. One such device belongs to Syndey University; the other, which was put into operation fully in 1973, to the Yakut Institute of Cosmophysical Studies. The important feature of the latter device (Fig. 11) is that it is supplied with special detectors of light flares, caused by so-called Cherenkov illumination of electrons at a speed greater than that of light. As earlier studies of Muscovite and English physicists showed, rather simple Cherenkov detectors (working, it is true, only on moonless and cloudless nights) can in principle give very valuable supplementary information on the picture of vertical development of a broad shower. This is connected with the fact that the narrowly /31
directed Cherenkov light is collected from the entire layer of the atmosphere, while ordinary measuring detectors are "sensitive" only to direct falls of charged particles.

Preliminary results of the work of the Sydney and the Yakut devices stand as proof of the existence of broad showers from particles with energies of approximately 10^{20} eV (and perhaps several times greater). The problem of the origin of particles of such high energies remains so far open. It is not out of the question (as G. T. Zatsepin noted) that these record showers were caused no longer by protons or nuclei, but by neutrinos -

particles which at lower energies have too weak an interaction with atomic nuclei of the earth's atmosphere.

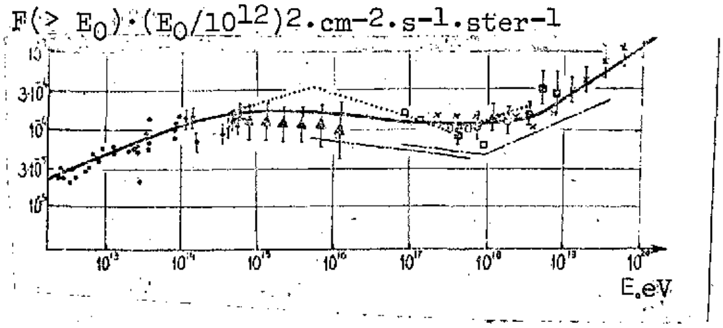

Fig. 10. An integral energy spectrum of primary particles of borad atmospheric showers according to data from various authors. For convenience of analysis, all ordinates were multiplied by the squares of the energy.

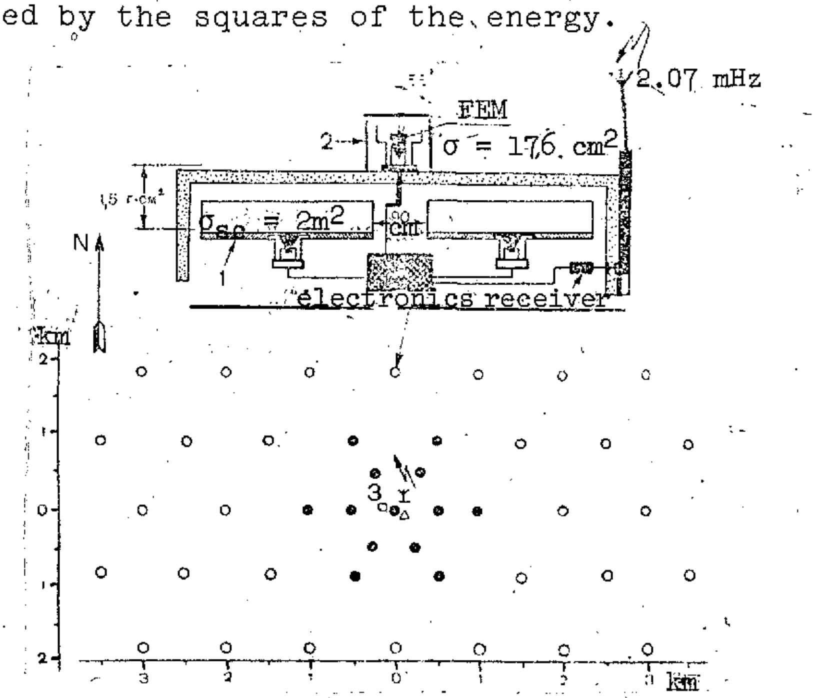

Fig. 11. Diagram (simplified) of the device of the Yakut Institute of Cosmophysical Studies for investigation of broad showers: 1-- scintillating measuring devices for electrons; 2-- detectors of Cherenkov illumination; 3-- measuring devices of penetrating particles. In the upper part of the drawing a scheme for a standard point for registration of a shower is shown.

On the Threshold of Future Accelerators

The greatest energy to which modern accelerators speed up particles is 400 GeV ($4 \cdot 10^{11}$ eV). It was achieved toward the end of 1972 in an accelerator in Batavia (near Chicago) in the USA. It is possible to increase the effective energy of two colliding protons by a factor of 4 in the accelerator of the European Center for Nuclear Research (CERN). In the CERN accelerator in 1972 engineers and physicists learned how to accelerate, heat, and collide with one another powerful bundles of protons. And although the energy of the protons in each of the bundles did not exceed 30.0 GeV, when they collide 60 GeV of energy may be used, inasmuch as (in contrast to the usual accelerator) one does not have to expend here an overwhelming part of the energy on the output of the immovable partner of the collision. /32

Thus, the interactions between particles with energy higher than $2 \cdot 10^{12}$ eV (sometimes designated at 10^{12} eV = 1 TeV) may be observed so far only by means of cosmic rays. And a thousand-multiple range of higher energies (approximately up to $2 \cdot 10^{15}$ eV) has already been studied directly, while the still more distant, approximately million-multiple range has been studied only indirectly, during the phenomena arising in the development of broad atmospheric showers.

With the influence of cosmic rays on the matter of the atmosphere of the earth, a complicated complex of transformation of particles occurs, caused by three principally different classes of interactions: the strong, the electromagnetic, and the weak.

Various examples of electromagnetic processes (including the release of Cherenkov radiation of charged particles) were discussed in the previous section, weak interactions will be discussed in a future section, and here we will dwell on the strong interactions in cosmic rays[1]. /33

The basic process of strong interaction may be written in the form of a reaction of multiple birth of particles:

$N + A \rightarrow A' + kN' + l\,\pi^{\pm} + m\pi^{0}$.

The nucleons are here designated by N, N' (protons or neutrons); A, A' designate the atomic nuclei, $\pi^{\pm}$ the charged π-mesons (or pions); π^{0} the neutral pions; k, l, m - whole numbers, of which l and m characterize the so-called multiplicity of birth of the new particles - the pions.

In contrast to experiments on accelerators, the cosmic experimenters had to deal with complex, although relatively light nuclei, since as a rule, they conduct very lengthy experiments at stations high in the mountains, where the use of liquid hydrogen is extremely difficult. Only one day in the history of studies of multiple birth was liquid hydrogen used. This bold attempt was made by the group of the American physicist L. Jones in 1969-1970 at the high-mountain station of Echo Lake, but for several reasons the results obtained by this group turned out to be mistaken.

The scientific tastes of experimenters differ rather strongly also in regard to the registering apparatus. One of the "classic" instruments in accelerators - a bubble chamber (in particular, a liquid-hydrogen chamber), is an instrument based on the phenomenon of the formation of bubbles of steam from an overheated

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[1]It has long been customary to call all particles capable of strong interactions of cosmic rays nuclear-active, but recently a short term for them has been established - "adrons" (first proposed by the Soviet scientist L. B. Okun).

liquid in those places where the charged particle flying past left ionized molecules of the liquid. Unfortunately, the bubble chamber has too short a "memory," (due to the short life of the ionized molecules), and thereforeitis impossible to release it "post factum" - after a cosmic particle accidentally falls into it.

At that same time not long ago, Wilson chambers were popular among cosmic researchers (instead of steam bubbles of a liquid droplets of liquid from supersaturated steam are formed in the ions), and also nuclear photoemulsions. Both of these are violently rejected by accelerator physicists: the Wilson chambers because of their slow action and especially the great amount of "dead" time, the photoemulsions also because of the complex composition of the nuclei which are incuded in them (basically they are heavy nuclei of silver and bromine). In experiments on broad showers, however, where very great areas for the equipment are needed, the basic instruments remain counters (previously these were "slow" gas-discharge ones, and now, as a rule, they are faster, scintillating ones). /34

In the lastthree to five years substantial progress has been noted in the development of measuring apparatus both for accelerators and for cosmic rays. In the first place requirements of working faster, more accurately, and more cheaply are in the forefront. Therefore, a relatively slow and very expensive instrument like a large bubble chamber has already been supplanted to a significant degree by another tracking instrument, a so-called streamer chamber, in which traces of charged particles are formed in numerous, rather thin and short streamers - electron showers, which define the initial stage of a spark discharge in the gas. Even more promising are the purely electronic (non-track) instruments with constant electrical feeding (but not impulse, as in the spark chamber). These are multiple-feed, proportional chambers, an improved variation of them being drifting chambers. We are speaking here of instruments in which the electrical charges arising in the gas when the charged particle flies past collect onto close-lying thin metallic threads, and then with proper accuracy (≈0.1 mm) the passage locus of these particles can be fixed quite well (~10^{-8}/sec), i.e., the moment of its flyby (to pinpoint the time in the drift chamber the knowledge of the near uniform drift velocity of the collecting charges in the electrical field near the cross wires is used).

For cosmic rays the chief demands are formulated briefly thus: the larger (in dimensions), as reliable as possible (in lengthy operation), the simpler and cheaper. Therefore, in particular, the long, narrow (with a diameter of 5 - 10 mm) pipes, filled with gas, proposed by the Italian physicist Conversi, are becoming more and more popular - radiation is excited in them as in neon tubes used in advertising, but only during flypast of an ionized particle. No less simple an instrument is the X-ray film, covered with a layer of lead; when an electron or photon of high energy ($>10^{12}$ eV) falls onto the lead, a narrow electron shower develops, making on the developed film a small (diameter of up to 200 μ) black little spot, by photomeasurement of which the energy of the initial particle may be determined. With both the Coversi tubes and the X-ray film it is possible without special expense to cover huge areas (many tens of square meters), thus preparing "traps" for very rare particles of superhigh energy, traveling in a stream of cosmic radiation. /35

A variety of scientific tastes create various possibilities in regard to the results of the studies, also. Space scientists base their conclusions on tens or hundreds of registered events of various energy, and only rarely (in experiments with BAS) do they operate with thousands. In accelerators data is obtained in strictly identical initial conditions on many thousands, and sometimes even millions of events.

This is why something in the manner of distant reconnaissance falls to the lot of cosmic researchers, yielding preliminary, as a rule, not always sufficiently explained qualitative data on a new field of phenomena, and this data is obtained by comparatively simple and cheap methods.

One of the simple and, at the same time, very typical features of multiple birth of particles in nuclei is a cross section of this process, designated usually by the symbol σ. It is determined on the one hand, by the radius of action of corresponding forces-those same forces which hold back the nuclons in the atomic nucleus - and on the other hand, by the degree of opacity of the nucleus for the strongly interacting particles - adrons - which fall on it. For a quantitative determination of the cross-section, it is useful to introduce an auxiliary quantity - the so-called mean free range of interaction λ. This range is inversely proportional to the probability of nuclear interaction of the given particle in a column of matter with a cross-section of 1 cm^2 and a weight of 1 g, and it amounts to $\lambda = 1/\sigma N_0$, where N_0 is the complete number of atomic nuclei in this column.

In this case it turns out that the stream of non-interacting primary protons in the atmosphere should decrease with depth x according to the exponent: /36

$$N(x) = N(x=0)\, e^{-x/\lambda},$$

N(x = 0) --is the stream on the boundary of the atmosphere.

A group of physicists from Moscow State University (N. L. Grigorov et al.) measured for the first time the stream of adrons on the tops of mountains with energy of $\sim 10^{12}$ eV, traveling without the accompaniment of any "products" of interaction in the atmosphere. By this method they showed that the mean range of inelastic interaction (associated with multiple birth of particles) is not more than 80 - 85 g/cm^2 instead of the 96 g/cm^2 observed in accelerators with an energy of 10^{10} eV. This means that the section of the nucleus of air must increase with energy by 15 - 20%, i.e., the nucleus seems to "swell" as the energy of the bombarding particle increases. It is not possible to explain this effect by an increase in opacity of the nucleus, for, as observations of processes of the diffractional type show, with energies of 10^{10} eV, the nucleus is practically completely opaque for the adrons (nucleons and Mesons) /37
faling onto it.

The data on ranges in the atmosphere were confirmed by the same group of physicists by direct measurements of the same ranges in a dense material (graphite) located directly in the upper part of the apparatus (Fig. 12) on satellites of the Proton series. This time the upper boundaries of the ranges were no longer obtained, but their exact amounts. After recalculation for sections of interaction of σ with nuclei of carbon and comparison with the data obtained in accelerators with an energy of 10 GeV, the following dependency of δ_c on energy was found:

$$\sigma_c = \sigma_0[1 + \alpha \ln(E/E_0)],$$

where a = 0.04, $E_0 = 10^{10}$ eV. Physicists working (under significantly purer conditions) in accelerators greeted these data with strong distrust. Despite the fact that they related to a complex nucleus of carbon, all theoreticians prefer to deal with the elementary processes of particle collisions: it was difficult to overcome the impression of the constancy of proton-proton sections in a broad interval of energies, from approximately 30 to 70 GeV. In addition, the theoretical predictions also, based on an analysis of accelerator data up to 70 GeV, it would seem, did not give a basis for predicting any substantial (even 10%) increase in cross-section up to 1,000 GeV.

A sharp reversal in the scientific public opinion came in 1973. By this time measurements were made of cross-sections of proton-proton interaction by three independent methods, in oncoming beams of the accelerator in CERN (Geneva), in which they succeeded in obtaining energies equivalent to energies of up to 2,000 GeV (in a laboratory system of coordinates).

To general surprise, these new data demonstrated with certainty the increase in the complete cross-section (and together with it, of the cross-sections of elastic and inelastic interaction also) at least by 10% - from 38.5 to 43 millibars (Fig. 13). Instead of the logarithmic increase discovered in cosmic rays, there was noted an even steeper increase in the cross-section, proportional to the square of the logarithm of energy.

It must be noted that it was the quadratic-logarithmic increase in the cross- section which previously was considered extremely admissible from the point of view of the most general, almost error-free principles of quantum theory. /38

An even simpler, but less important characteristic of multiple birth of particles is their number. It is simplest of all to measure the number of charged particles released from the point of interaction, and then it is possible to consider that, of them, on the average, $K \approx 1.4$ particles for proton-proton (pp) and $K = 1$ particles for proton-neutron (pn) interaction, should be protons.

Inasmuch as in accelerators multiplicity is measured exactly for pp-, and sometimes for pn-interactions, in experiments with cosmic rays they try to ensure such conditions so that the target for the particle bombarding the nucleus is a single, quasifree nucleon of the nucleus. With an even number of particles engendered, this should be a proton, with an uneven number - usually a neutron, although sometimes (let us say with the multiplicity k + 1 = 3, this can turn out also to be a process of the diffractional type, occurring in the nucleus of the target as a whole.

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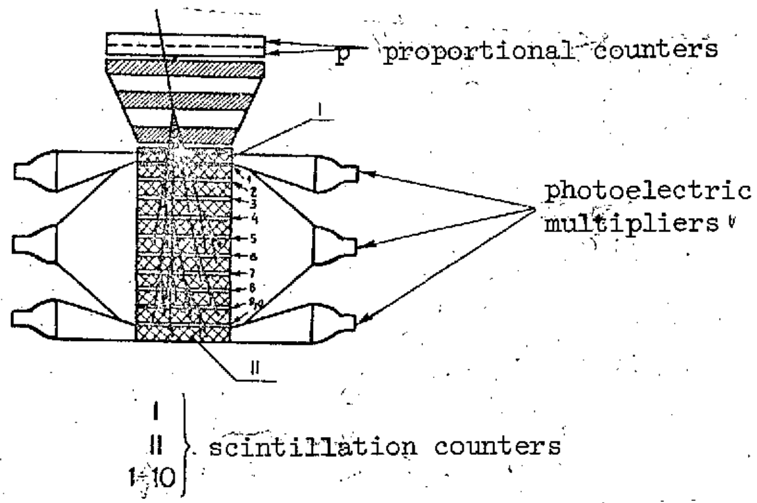

Fig. 12. Device at Moscow State University for measurement of the energy spectrum and cross-sections of strong interaction of particles on Proton satellites.

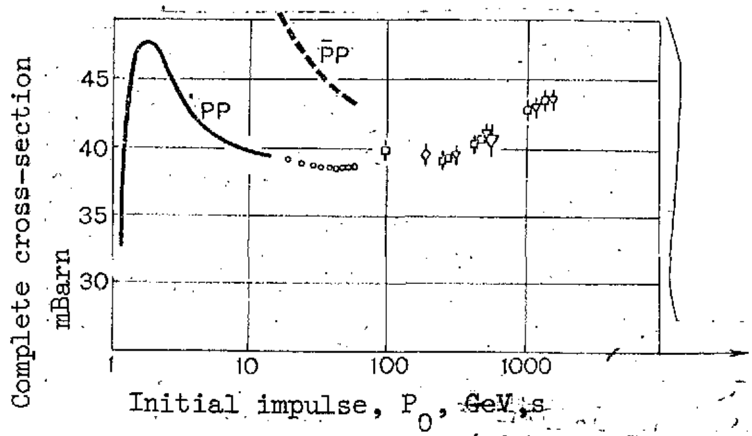

Fig. 13. Contemporary data (obtained in various accelerators) on increase in the complete cross-section of interaction of protons (PP) with an increase in their initial impulse P_0P. For comparison, sections of interaction of antiprotons ($\bar{P}P$) are shown.

In Fig. 14 a summary of measurements of multiplicity is /39
given at first in accelerators (up to energy of $2 \cdot 10^{12}$ eV), and then (with energies of up to 10^{13} eV) in comsic rays. It is apparent that the general course of multiplicity is laid out on a single smooth curve. Beyond the bounds of the curve those very data on cosmic rays (from a group of L. Jones) which were obtained, it would seem, under the purest conditions - in liquid hydrogen - fell noticeably.

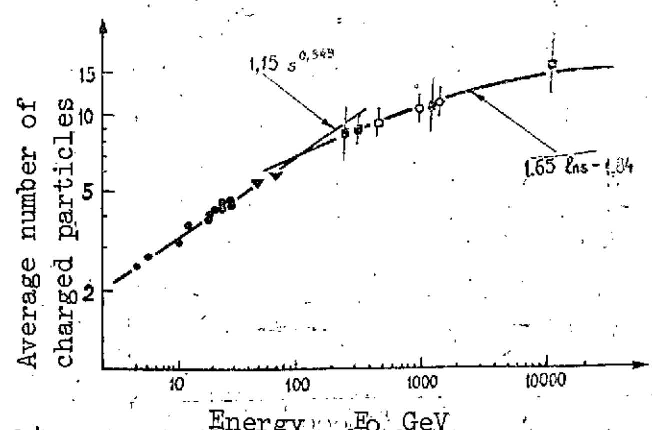

Fig. 14. Dependence of the average number of bred charged particles on the energy E_o of the colliding particles (adrons).

Inasmuch as the error in the data of L. Jones is now already generally accepted (the reasons for the error will not be discussed here), it is possible to try to give an analytical expression for all the remaining data. This expression has a simple stage form with energies E of approximately up to 70 - 100 GeV ($n_{\pm}$ $E^{1.3}$), and with higher energies, a somewhat more complex logarithmic form ($n_{\pm} = A + B \log E$).

The emergence of multiplicity to a logarithmic law makes the theoreticians rejoice who are developing various models of interactions of a peripheral type, in which the process of interaction is treated as a result of the successive substitution of interacting particles by special "auxiliary" ones, so-called virtual particles.

But this result is unacceptable to adherents of the hydrodynamic model, who have a theory of the formation of a single strongly excited cluster of meson matter, falling according to the laws of the hydrodynamics of very fast (relativistic) particles. /40

To be sure, the situation is made more complex by the fact that the data on the development of extensive showers coordinate poorly with the logarithmic dependence and apparently indicate a faster increase in multiplicity with energies higher than $10^{13} - 10^{14}$ eV.

Other data on broad showers, connected with the discovery in them of comparatively strongly delayed particles (in comparison with the chief mass of particles - electrons), were the first indication of one important feature of multiple birth. It consists in the increase with energy of the number of heavy particles, apparently nucleons, and possibly also of their "partners" - antinucleons.

Very recently, in 1972, in an accelerator with oncoming beams, this indication was excellently justified. It turned out that among the negatively charged particles in the transfer from energies of 10^{10} to energies of $\sim 10^{12}$ eV, the proportion of antiprotons increased very greatly (5 - 7 times). This result may be qualitatively and even quantitatively explained on the basis of one more model of the process, taking into account that among the structural elements of nucleons (as well as mesons) there are pairs of special particles - quarks and their antiparticles - antiquarks[1] - which are closely connected with one another. With an increase in the energy of the onrushing particle, the energy of communication of the antiquarks becomes less and less substantial, and therefore the relative number of bred mesons, nuclons, and antinucleons begins, to a greater and greater degree, to be determined by a study of combinations of various bonds of quarks and antiquarks.

The Evolution of a Fireball. Reality and Guesses.

The simplest and most obvious, sufficiently accurate, although /41 also very laborious method for the study of processes of multiple breeding of particles in cosmic rays were thick-layered nuclear emulsions. People learned to produce these emulsions a long time ago in the form of unsupported layers 400-600 μ thick with horizontal dimensions of up to 30 x 40 cm^2 (and sometimes more). From such layers many times solid piles were collected with a volume of up to 50 - 80 l., which were later lifted to the upper layers of the atmosphere with the help of ballons, and one day even byond the bounds of the atmosphere - on an artificial earth satellite (this was the collective experiment by scientists of a number of socialist countries on the Interkosmos-6 satellite).

Among the scientists who occupied themselves a great deal with the study of multiple breeding of particles at high energies (>1 Tev)[2] by the method of photoemulsions, were the Cracow group, headed by M. Ya. Mensovich, the Tokyo group, headed by K. Niu, and others. These physicists as early as 1957 considered the

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1. This is the term used for hypothetical particles of three types, still undiscovered in free form, for which it has become customary to ascribe a fractional electrical charge (equal to 1/3 or 2/3 of the charge of an electron) and a very large mass (not less than 5 - 10 masses of a nucleon).

2. In the system of the center of inertia of colliding particles, this corresponds to an energy of $\approx$50 GeV.

following surprising peculiarities of the processes they had observed.

In the first place, all the bred charged particles (they were, as a rule, mesons, or pions) were divided seemingly into two groups, in each of which there occurred an equal dispersion according to angles (isotropic) of particles from a single center.

In the second place, the distribution of particles according to energies and impulses in each such group approximately corresponded to the spectrum of radiation of an absolute black body (Planck's law), heated to a temperature of approximately 1 - 2 trillions of degrees (about 150 MeV in energy units); and the mean energy of each particle constituted about 0.5 GeV, while that of the entire group was 3 - 5 GeV.

In the third place, the total energy, divided into two groups of particles, constitutes only a small part (on the average, ~30%) of the energy of the initial adron (in particular, a proton), which remains after the interaction of the particle produced according to energy (sometimes called the leading particle). /42

For an explanation of all three peculiarities at once, these researchers, independently of one another, advanced the hypothesis[1] of the existence of a so-called fireball ("fiery ball" in translation from the English), i.e., of some kind of very unstable highly excited physical object, almost instantly disintegrating into individual, much more stable elementary particles - pions.

A group of physicists from the P. N. Lebedev Physical Insti-

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1. The Italian physicist G. Cocconi developed similar views.

tute (N. A. Dobrotin, S. A. Slavatinskiy, and others), who studied the processes of multiple breeding of particles at lower energies (hundred of GeV) by means of a Wilson chamber in a magnetic field, came to a similar conclusion. Some new aspect, not so much in principle, was the fact that under these conditions not two, but only one fireball was observed, as a rule.

Still another, at first unnoticed peculiarity of the phenomenon was that, together with the basic mass of particles deposited in the framework of the Planck spectrum, it was necessary to note the small number of particles which are close in speed to the leading particle (proton).

Following the views which were developed by G. T. Zatsepin (USSR), S. Takahi((Japan), Ya. Pal (India) and other physicists, the first hypothesis on the fireball at the beginning of the 1960s began to be supplemented by a hypothesis on the excitation of nucleons participating in the process to the state of a heavier, unstable particle - an isobar.

It must be noted that the hypothesis of fireballs was many times subject to doubts and more or less sharp criticism on the part of other specialists on multiple breeding of particles, and especially those who conducted their own studies in accelerators. This criticism arose first of all from the insufficient accuracy and completeness of the data given by the cosmic researchers /43
and furthermore, from the abundance of other theoretical models describing the basic features of the phenomenon, in general, no worse, and in some cases obviously better than, the model of fireballs.

It gradually became clear that for a choice in favor of one or another model of the phenomenon it is not enough simply to wait until a new "generation" of accelerators begins operation, calculated to produce strong interactions with energy of up to 1

TeV. Although this process is extremely important, it is nevertheless very useful to try to "feel," even though roughly, the field of higher energies - up to 10^{14} eV (100 TeV). Actually, even with energies of nucleons of $\sim 10^{12}$ eV, the explosion at speeds (more exactly, at so-called Lorentz-factors, giving the relation of the complete energy of the system to its energy of rest mass) between the "classical" fireball and the nucleon isobar is still not very great; therefore, it is not easy to divide the products of their disintegration among them. The task is made substantially easier if the energy of the same isobar (and for this also the energy of the primary particle) increases by a factor of 10. This was approximately the course of the deliberations which inspired a group of Soviet physicists headed by Yu. A. Smorodin, and independently of them, a large Japanese-Brazilian group (Fujimoto, S. Hasegawa, and others) to set up a new series of studies.

The experiments, however, were based on the use of photoemulsions, but now in a new variation. Instead of thick blocks of pure nuclear emulsion, they placed in the apparatus something like a giant "Napoleon" of alternating layers of lead (1.5 - 2 cm each), a thin nuclear emulsion, and a highly sensitive X-ray film. The idea of the experiment is to register and measure the beams of γ-quanta of high energy which arise with the multiple formation and decay of π^o- mesons in some kind of suitable target over the apparatus, whether it be a special layer of light material or simply atmospheric air. The X-ray film allows the discovery of little black spots engendered by the narrow clusters of cascade-multiplying electrons in the lead from every γ-quantum of sufficiently high energy (~ 1 TeV and higher); but the nuclear emulsion just adjacent to it helps to determine the energy and angles of fall of these γ-quanta, and partily also to find new, weaker electron cascades, thereby lowering the energy /44
"threshold" for the registration of γ-quanta and π^o-mesons.

The Soviet and Japanese-Brazilian experiments unanimously established the fact that all (or almost all) the γ-quanta of high energy are engendered in nuclear interactions of superhigh energy through an intermediate stage of the formation and decay of some, as a rule, moderately heavy bundles of strongly excited matter, which may, following tradition, be called fireballs. In addition, in some cases (especially with energies of $\gtrsim 10^{13}$ eV), it is apparently necessary to also take into account the formation of some substantially heavier "superfireballs," which can in a cascade (stepwise) manner disintegrate into lighter fireballs at the beginning, and then into individual particles - pions (both neutral and apparently also charged).

Meanwhile the new, superpowerful CERN accelerator (Geneva) was working full force, allowing the study in detail of the interaction of oncoming proton beams, equivalent to cosmic particles with an /45
energy of up to 2 TeV. By the beginning of 1973 a huge amount of data had been obtained in it on impulse and angular characteristics of the process of multiple breeding of particles. In particular, the property of scale invariability[1] was established, i.e., a kind of impulse distribution of the bred particles (more accurately, of distributions of longitudinal components of their impulse) with various initial energies of the protons E_o.

Meanwhile, as the calculations of Smorodin (Fig. 15) showed, it is possible to ensure a fairly good agreement with accelerator data for the proper form of a "regulated" model of fireballs. It is necessary to consider, in particular, the fact that together with a swift fireball with a mean mass (~3.5 GeV) that does not depend on the energy E_o, a slow fireball (in 50% of the cases)

1. This property was given the name of the English term scaling (from the word "scale").

is also produced, the mass of which slowly increases with energy E_o ($M \sim \log E_o$).

A serious confirmation of the model of fireballs (which now already exists in several variations) was a new series of experiments on accelerators in Geneva and Batavia (USA), in which the correlations, i.e., the mutual dependence of particles bred with various impulses and angles of emission, were studied in detail.

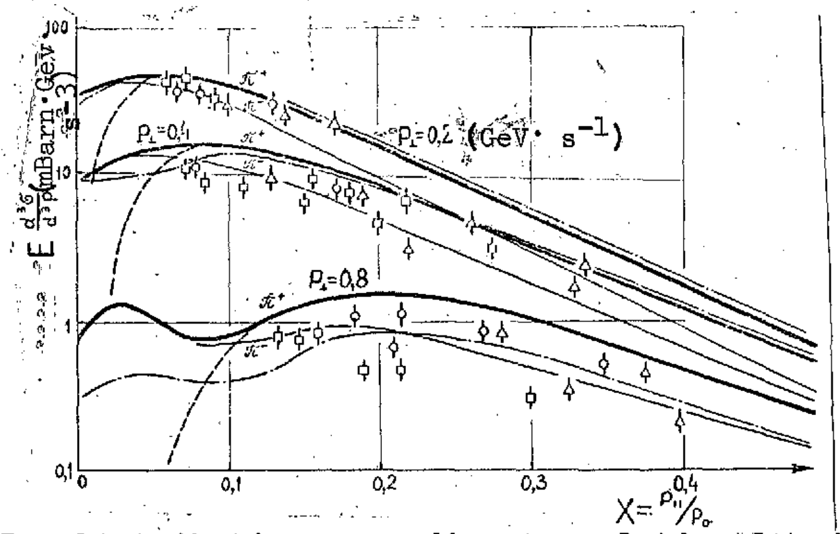

Fig. 15. Distribution according to relative longitudinal impulses of π^+ and π^- -mesons according to data of an accelerator with oncoming beams and results of corresponding calculations of Yu. A. Smorodin according to the model of fireballs (continuous curves).

The Physics of Penetrating Particles

The exceptionally high penetrating ability of cosmic rays (kilometers into the depth of the earth), as is known, is connected with the presence in their composition, in the first place, of μ-mesons (muons) of very high energy (more than 10^{12} eV), and secondly, of neutrinos of various energies. The registration of both types of particles has been up to the present extremely difficult for two reasons. In the case of muons this is due to the sharply falling spectrum with increase in energy E (it has

the form of approximately $N(E)\ dE\ E^{-2.5}dE$); in the case of neutri- /46
nos, also the very low amount of the effective cross-section of their interaction with matter (at any energies). In both cases not only the measurement, but even an approximate estimate of energies of each of the particles is by no means a simple task; but we will not dwell here on this aspect of the experiment.

The greater part of the recent studies relating to the properties of muons of high energy consists in the study of their energy (with a prescribed direction of fall) or angular (with a prescribed energy) distribution. If in addition the sign of the charge of the muons is determined, this gives substantial additional information.

It is important to compare the data on energy distribution of muons (more exactly, the absolute amount of the stream of muons as a function of their energy) with similar data for the proton and photon component of cosmic rays. Their analysis shows that a significant part of the energy of a proton in the process of multiple breeding of particles is transmitted to a small number of charged ($\pi^{\pm}$) and neutral (π^{0}) mesons, the decay of which (according to the schemes $\pi^{\pm}\rightarrow\mu^{\pm}+\nu$ and $\pi^{0}\rightarrow 2\gamma$) gives a beginning for muon and photon components of cosmic rays. This fact may be explained intellectually by the above-mentioned hypothesis of Smorodin on the excitation of a fast proton falling into a nucleus up to an intermediate, very short-lived, unstable state with an increased mass (in the order of 3.5 GeV in energy units). In the scientific literature various variations are also often discussed of the model of the so-called extreme fragmentation of adrons proposed in 1970 by the well-known theoretician Young in the USA. The model is based on the fact that each of the "partners" of strong interaction undergoes excitation independent of one another and subsequent decay independent of the complete energy of collision E_0 with a single condition that the energy E_0 is already sufficiently high.

In experiments on angular distribution of muons, it is possible in principle to "feel" the nature of those intermediate particles which are, on the one hand, the direct "product" of strong interaction, and on the other hand, precursors of the observed muons. Actually, from experiments in accelerators it is known that sometimes in strong interactions there are bred not only $\pi^{\pm}$, /47 but also $K^{\pm}$ -mesons, the decay of which in 95% of the cases leads to the appearance of a muon. In contrast to the pions ($\pi^{\pm}$), the kaons ($K^{\pm}$) swiftly decay and more rarely (with a smaller cross-section) are absorbed by strong interactions with the nuclei of the atmosphere. Therefore, for kaons, as the angle increases with the vertical θ, the decrease in effective density of the atmosphere will not have such a strong infuence as for the pions. The stream of muons being formed will depend sill more weakly on the direction of their movement (the angle θ) if they are bred directly or through an intermediate particle with a lifetime which disappears in a short time.

Experiments conducted up to recently have allowed us to come to two conclusions of a semiquantitative character:

1. The relative contribution of kaons to the generation of muons, if it increases in comparison with the field of accelerator energies, does so not very substantially (a maximum of 2-3 times).

2. The contribution of direct generation (including through short-lived particles) has not, in general, been proven, although indications present allow us to speak of the probability of such a process of $\sim 2\%$.

The question of the direct or almost direct generation of muons with very high energies is especially interesting in connection with new ideas in theoretical physics in regard to the possibility of combining theories of weak and electromagnetic interaction of particles. Up to now it has been thought that the cross-section

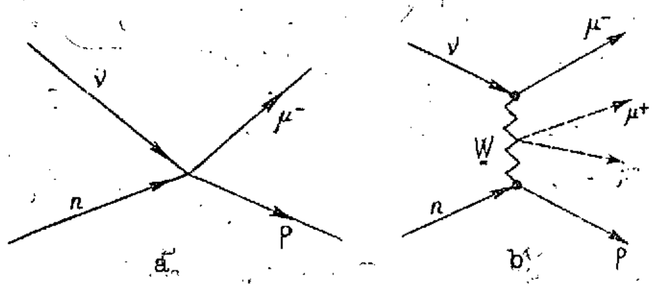

Fig. 16. An "orthodox", 4-Fermi (a) and a new model of weak interaction of particles, with the participation of a W-boson ((b).

of weak interaction must increase proportionally to the energy of the colliding particles, right up to very high energies, /48 and, possibly, up to such energies at which weak interaction can be compared with strong. Here, a model of substantially "contact" interaction of four particles (Fig. 16a) was used, including initial and final particles, as, for example, in the process $\nu + n \to \mu^- + p$, where μ is a meson, n a neutron, ν a neutrino, p a proton).

Mathematically this interaction may be presented and calculated similarly to the interaction of two electric currents which, besides the amounts of the two electrical charges e_1, e_2, are proportional to their velocities v_1, v_2 (for current I = eV).

It turned out that the "cutting" of the cross-section of weak interaction (on the level of the section of the electromagnetic) may be obtained in a natural manner if we introduce into the discussion a hypothetical heavy vector (i.e., one which has angular momentum h similar to a photon) particle, which is a virtual carrier of weak interactions and can decay into two weakly interacting particles, including a muon (Fig. 16b). The physical idea of the new model consists in the "contact" character of the interaction being preserved until the wavelengths of the colliding particles (inversely proportional to their impulses) are large in comparison with the effective "radius of action" of the virtual carrier of interactions, which, in its turn, is inversely proportional to its mass M_o. When the impulses and energies of the colliding particles increase, it is necessary to take into account the so-called function of interaction propagator with which the sum of the squares of the mass M_o and the impulse transferred with the interaction of impulse K goes into the denominator. In that field where the condition $k \gg M_o c$ is not yet fulfilled, the function of the propagator stops the further growth of the interaction cross-section. The whole situation in this extreme case turns out to be analogous to that of electrodynamics, in which the mass of the virtual carrier of interactions (the photon) is also considered the final magnitude.

The mass of the new hypothetical particle, given the designation W-boson,[1] is obtained in this model with approximately 40 GeV (in energy units), i.e., 40 or more times greater than the mass of the nucleon. At the same time, the possibility is also foreseen of "almost direct" generation of muons by strongly interacting particles, if their energy in the system of the center of inertia becomes sufficient for the formation in free form of a boson + antiboson ($W + \overline{W}$) pair. /49

Cosmic Rays and the Search for Minerals

The high penetrating ability of cosmic muons in combination with the very simple law for their energy losses (connected chiefly

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1. Depending on the amount of their own mechanical moment - the angular momentum - all elementary particles are divided into bosons (which have a zero or integral-number angular momentum (in units of Planck's constant h) and fermions (which have a semi-integral angular momentum).

with the ionization of matter) makes them a rather convenient and effective instrument for solving some problems of the national economy. All these tasks - the search for minerals, the discovery of vacuums in mining, the determination of loads in a tunnel, etc., are connected in one way or another with the illumination of large layers of matter with cosmic rays. For solving problems of practical importance on admissible thicknesses of matter and for the sensitivity of the method itself, it is sufficient to use well-known curves of absorption of cosmic rays in water or in soil (Fig. 17).

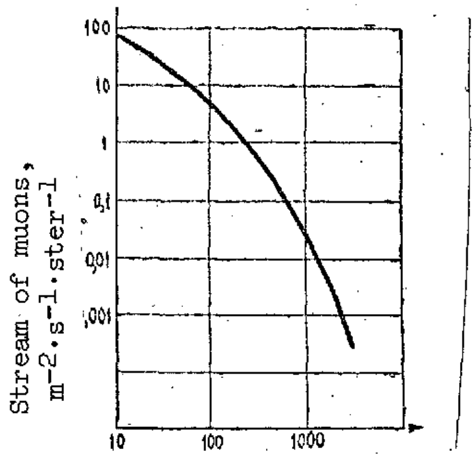

Fig. 17. Absorption of the penetrating component (muons) of cosmic rays in soil. The depth is expressed in equivalent thicknesses of a layer of water.

From these curves, plotted in logarithm to base 2 scale, it is apparent, in the first place, that at the beginning the absorption of muons occurs comparatively slowly: with an increase in depth by a factor of 5, from 20 to 100 m of water equivalent /50 (or from 10 to 50 m of soil with a density of 2 g/cm^3) the flux of muons decreases 10 times. In a small interval of thicknesses this will signifiy an increase in total mass of the matter, let us say, by 5%, will lead to a perceptible decrease in the radiation flux to 10%. In turn, a 5% change in the total mass is obtained, for example, if in a 50-meter layer of soil with a density of $\rho_0 = 2 g/cm^3$ a layer of ore is wedged in, with a thickness of 5 m and a density of $\rho_1 = 3 g/cm^3$.

The second conclusion from the absorption curves consists in the determination of the necessary duration of measurements according to their prescribed accuracy and prescribed depth of observations. Thus, at a depth of 100 m in water ($\sim$ 50 m of soil) the stream of cosmic rays is $N_0 \approx 2$ particles in 1 m^2 in 1 s with a working solid angle of the instrument $\omega_0 = 1$ steradian. If it is taken into consideration, thereby, that the accidental fluctuations (oscillations in time) of the flux N consist, expressed relatively, of $2\sqrt{N}$*, then it is easy to become convinced that an instrument with an area of $S = 1 m^2$ can ensure 10% accuracy for t = 200 s of measurements, for with this $N = StN_0 = 400$ and $2\sqrt{N} = 0.1$.

The third conclusion consists in the gradual increase with depth of the relative speed of absorption of the stream of radiation and, simultaneously with this, in the constant increase in the necessary duration of measurements due to decreasing intensity of the stream. As a typical example we note than an increase in depth from 300 to 1000 m of water equivalent (a total of three times) reduces the intensity of illumination almost 30 times. From this it follows that the same 10% accuracy of measurement is required for discovery of a 5 meter layer with excess density of $\Delta\rho = \rho_1 = \rho_0 = 1 g/cm^3$ even at a depth of 500 m in water (or $\approx$ 250 m of rock). But in addition, at this depth the radiation flux consists of a total of 0.05 particles in 1 sec through the same instrument ($S = 1 m^2$, $\omega = 1$ steradian), and therefore the 10% level of fluctautions will be reached, as it is easy to calculate, with only a duration of measurements of abut 8000 s, i.e., more than two hours in one point of observation.

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*This means that fluctuations exceeding this amount may occur only with a probability of 5%.

Deliberations of the type presented above were well proven under real conditions by V. M. Bondarenko's group from the Moscow Geological Survey Institute as early as the beginning of the 1960's. This group went off, in particular, on an expedition to one of the copper pyrite deposits of the Central Urals, and later, to an iron-ore deposit in Central Asia. In the latter case, the problem was complicated by the necessity of taking into account the rather sharply expressed relief of the surface of the earth; in addition, the thickness of the ore deposit itself (magnetite) was only about 20 m instead of 120 m in the first case. Nevertheless, in both cases the results of the measurements of the flux of cosmic rays in the horizontal adit under the ore bed turned out to correspond very well with the data from a usual, much more laborious geological survey. /51

Experience has shown prospecting with cosmic rays is especially effective in combination with gravimetric survey, based on very exact measurement of the force of gravity over the proposed ore bed. Actually, if the measurements are made in one and the same adit, gravimetry "feels" the influence of the total mass of the deposits lying under the feet of the bed, less the reverse influence of all the masses located above the head of the observer. But the masses lying above (regardless of the composition of the deposits) are subject to control with cosmic rays.

"Cosmic-ray prospecting" of ore deposits is especially useful in those deposits where adits may have already been made, but the degree of exhaustion of the reserves lying above remains insufficiently clear.

But this is by no means the only possibility for using the free source of penetrating radiation. Often it is extremely important to discover ore deposits no thicker than the surrounding rock, and, on the other hand, wastelands, in particular zones with karsts, filled with ground waters.

Interesting also are applied tasks from the field of engineering geology, in particular, the determination of the total load in underground tunnels (for example, in constructing subway lines). The fact is that a "telescope" of registering instruments, registering the cosmic radiation flux passing under the ground, permits the direct measurement of the total mass /52 of matter in the field of its "vision," including here both the known (simply according to the depth at which the tunnel lies) mass of soil, as well as the previously unknown weight of the building located under the tunnel.

Of course, the use of cosmic rays in survey and engineering geology requires careful calculation of all the advantages and shortcomings of this method. Its comparative cheapness, simplicity of data processing, insensitivity to interferences, and the high penetrating capability of the radiation are attractive.

It is necessary to categorize the inconveniences: first of all, the necessity of "looking" from below to above - from a rather deep, already prepared passageway. To be sure, even with simple drilling of vertical wells cosmic rays can give useful information on the density of rock (soil) at one time in large sectors of non-homogenous structure. By submerging into the drill-hole a comparatively compact registering device (let us say, a calculator of Cherenkov radiation of fast muons), it is possible to make a "survey" of the average density of the rock lying in a round cone from the top in a point of measurement, at an angle near the apex of about 45° and the base of the cone on the surface of the earth. Such measurements can in principle eliminate the necessity of drilling many holes for direct taking of probes in each of these holes.

The Secret of the Pyramid of Khefren

Not very far from Cairo, in Giza, rise three stone structures - grave monuments of the Pharaohs of the IV dynasty. The most modest pyramid was dedicated to the Pharaoh Snefer; to his son Cheops and grandson Khefren belonged gigantic pyramids each 145 m high, with sides of the base of 230 and 215 m, respectively. Thirty-four centuries after it was built the great pyramid of Cheops has become accessible to man's gaze not only from the outside, but also from within. As early as the ninth century A.D., the complex system of its burial chambers and underground passages was revealed (Fig. 18).

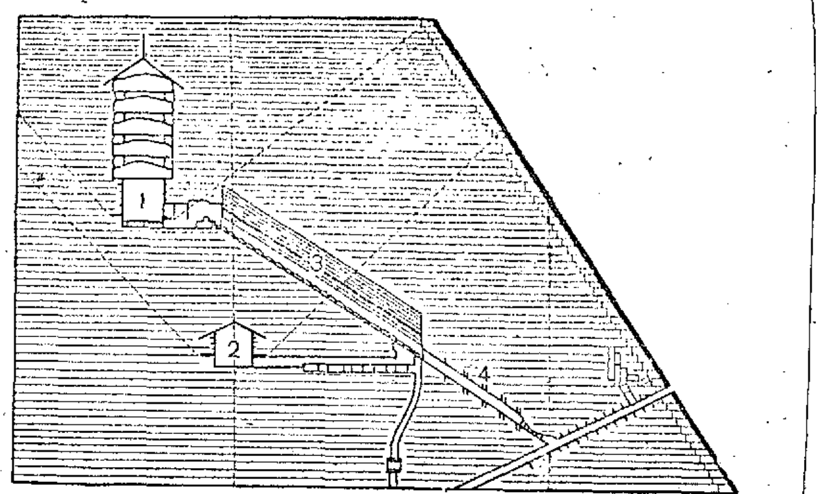

Fig. 18. Vertical section of the pyramid of Cheops: 1--bural chamber of the Pharaoh; 2--chamber of the Pharaoh's wife; 3-- large gallery; 4--communications passageway.

Ten centuries later, modest attempts were also made to penetrate inside the pyramid of Khefren. But, alas, they succeeded in finding nothing except the previously accessible Belsoni chamber (in the middle of the base of the pyramid). Historians and archaeologists gradually came to the conclusion that the great simplification in the design of the "interiors" is /53 fully explained by the change in architectural style of that time."

But perhaps this was not so, and the architects of Khefren simply wanted to hide the treasurehouse of their sovereign more effectively from future generations.

On this very subject hot disputes were conducted as early as 1965 between the well-known American physicist L. Alvarez and his friends from Cairo University, among whom was also the well-known researcher of the pyramids, archaeologist A. Fakhry. Let us take a look, Alvarez decided then, for it is certainly not accidental that cosmic rays exist in the world, and this obstacle is no more serious for hundreds of meters of rocks than the human body for X-rays in a clinic. Thus arose the joint American-Egyptian pyramid project, approved by authoritative organizations of both countries in June, 1966. /54

In the spring of 1967 the necessary registration apparatus was installed in the Belzoni chamber. It consisted of two series of spark chambers with an area of each series of about 3.2 m^2, and also of three rows of scintillation counters with a meter iron layer between them for separation of the most penetrating particles - muons with energies of more than 40 GeV. (It is interesting to note that these were approximately the energy capabilities of the Soviet accelerator in Serpukhovo.)

Calculations showed that, using the practically isotropic flux of muons with an energy spectrum which falls as an inverse quadrant of energy, it is possible, in principle, to note a 10% increase in "brightness" of the muon flux, if on its path a chamber is encountered which is similar to the king's chamber of the pyramid of Cheops. And for this, in turn, it was necessary, in the first place, to bring the angular resolution of the apparatus to at least 3°, breaking the entire field of view of the spark chambers into 900 cells, and in the second place, to ensure such a lengthy (over many months) exposure, that through every bin not less than 1.5 - 2 thousand penetrating parts pass. It was obvious that it would be practically impossible to process by hand data on the trajectories of a million particles and, therefore, an automated device in combination with an electronic computer on the level of the most advanced equipment was used to achieve success.

Two basic methods of presentation and analysis of the experimental picture of the "illumination" of the pyramid of Khefren were proposed. The first consisted in the construction of an artificial ("simulated," in the terminology of the authors of the work) X-ray photograph, which would imitate the image of the pyramid thrown by the imaginary source of the penetrating radiation from the Belzoni chamber onto a huge spherical screen lying on top of it.

The second, analytical method, consisted of the comparison of two maps with the experimental and calculated amounts of the fluxes of cosmic particles in each of the 900 cells of the field of view of the spark chambers transferred to them.

To the joy of the researchers, from the "X-ray photographs" /55 obtained from an analysis of the first series of measurements, the contours of something like the great hall of the pyramid of Cheops showed through, extending in the north-south direction. Unfortunately, the joy was not lasting. After scrupulous introduction of corrections into the geometrical configuration and uneven sensitivity of the apparatus, the image of the "hall" faded, and the contours of the corners of the pyramid showed through clearly. With an analytical presentation of the facts, they succeeded in clearly "sensing" also such a detail of the construction as the top "cap" from the undismantled two-meter limestone facing of the pyramid.

Finally, after the introduction of new corrections into the form of the external "outlines" of the pyramid, the whole field of the "simulated X-ray photograph" turned out to be unevenly gray. A detailed comparison of the experimental and calculated charts showed that in none of the cells was there a divergence of the experiment from the calculation which reached a quadruple level of mean statistical fluctuation (although one such fluctuation is still alowed with a probability of 1/3).

But perhaps the "exposure" of the apparatus was not yet sufficient for solving the problem raised, even within the bounds of the 19% of the volume of the pyramid that fell into the field of view? This suggestion was convincingly refuted by analytical imitation of the effect that would be obtained by showing on the path of the cosmic rays an empty place, analogous to the king's chamber of the pyramid of Cheops. Actually, on a "differential" map of the image of the pyramid, in this case, an extended spot of the dimensions of 4 angular cells on the horizontal (i.e., from east to west) and 2-3 in the vertical (from north to south), in which the "contrast" would exceed quadruple statistical fluctuation, would be drawn.

Thus, the pyramid of Khefren turned out to be actually a solid stone monolith, at least its chief central part. Indeed, the authors of the article, published in the February 1970 issue of Science, still did not exclude the possibility of discovering in the future something interesting in the remaining 80% of the volume of the pyramid.

The Pursuit of "Ghosts" in Mines

In 1968 the American physicist R. Davis et al. published /56
for the first time an interesting experiment directed toward the use of cosmic neutrinos for thermometry of the sun's interior. The idea of this experiment (inspired by the works of the Soviet scientist B. Pontecorvo) consisted in the registration of fluxes of solar neutrinos by a nuclear reaction in an isotope of chlorine Cl^{37}:

$$Cl^{37}+\nu \rightarrow Ar^{37*}+e^- .$$

Inasmuch as the cross section for this reaction (as for any weak interaction) is insignificantly small, the experimenters had to take a huge amount of chlorine-containing matter C_2Cl_4 (610 t or 390 m^3!), driving the whole apparatus deep under the earth (to a depth of 4400 m of water equivalent) in order to eliminate the already known background reactions caused by cosmic rays.

The chief difficulty of the experiment is to derive from such a large volume an insignificantly small number of unstable atoms of excited argon-37 and to pass all of them through a special low background counter, registering the decay of these atoms with well-calibrated efficiency ($\approx$ 50%).

Davis considered that with an internal temperature for the sun of 15 million degrees, the chief source of the neutrinos detected (for detecting an energy of ~6 MeV is necessary) is the reaction $B^8 \rightarrow Be^{6*} + e^+ + v$, which leads in his apparatus to a calculation rate of ~1 event in 24 hours.

Reality turned out to be not so "rosy": during the first 35 days of the experiment, the resulting effect turned out to be (with the deduction of background events) a total of -1 ± 5 readings; in the second series (of the same length), + 0.8 ± 4.

Such a serious discrepancy between the experiment and the predictions of the theory forced them again and again to think through and to check on each small detail in the experimental method (in order to increase the sensitivity of the apparatus) and each number used in the course of calculation of the neutrino "productivity" of the solar thermonuclear boiler. /57

Along both lines, serious progress has been made during the last ten years. On the one hand, Davis succeeded in reducing the background readings of the apparatus to 1 impulse per month, both by miniaturization of his proportional counter, and by using super-pure materials for its production.

On the other hand, theoreticians (chiefly Bacall engaged in this in the USA) made a complete revision of the estimates of the expected flux of neutrinos. In this case refined data on the cross sections of these reactions, determining the work of the sun's thermonuclear boiler were used, along with current data on the opacity of solar matter for the photons of thermal radiation which "cut through" from the center (this opacity determines the degree of thermal insulation of the thermonuclear boiler from the external shell of the sun).

Despite all the devices used, there still occurs today at least a quadruple "deficity" of solar neutrinos in comparison to theoretical predictions.

The corresponding conclusions in regard to the thermonuclear solar "boiler" also bear a negative character: it can be affirmed, in particular, that the temperature of the sun's interior does not exceed 15 million degrees, and that the carbon-nitrogen thermonuclear cycle (going through the isotopes N^{13} and O^{15}) is not the chief source of the energy production of the sun.

Even before many possibilities were exhausted for increasing the sensitivity of Davis' apparatus, the possible errors that raise the expected magnitude of the neutrino flux were, on the one hand, taken into account, while on the other hand, astrophysicists dashed off to search for basically new paths for the "escape" of the falling neutrinos.

The effects connected with the "dilution" of the sun's nuclear fuel with a light isotope of helium (He^3) and the possibility of cooling the sun's interior by a deep turbulent mixture of matter throughout the entire thickness of the sun, the increase in the relative contribution of competing reactions, and, finally, the completely extravagant hypothesis (advanced by the Soviet scientist B. M. Pontecorvo) on the pulsating character of the /58 spontaneous transformations of neutrinos from one state to another in the course of its flight from the sun to the earth were considered. Nevertheless, a sufficiently convincing explanation of the "discrepancy" between the expected and the observed (more exactly, the still unobserved) fluxes of solar neutrinos up to this time has not been devised by anyone. As before, it is difficult to understand how the sun succeeds in heating up its external shell to a temperature which ensures the huge power for the light flux which we observe, and at the same time, does not reach the expected high degree of "scorching", which is comparatively modest according to the dimensions of the central "furnace", where reactions of thermonuclear synthesis rage. To be sure, the certainty of the existence of the "discrepancy" itself is not so great: the really complex theoretical procedure of recalculation from the surface temperature of the sun ($\approx$6 thousand degrees) to the much higher temperature in its center ($\approx$14 million degrees), to which the expected fluxes of neutrinos are extremely sensitive, may turn out to be much less accurate than the authors of the calculations assert.

In the near future, it is evident, people will succeed in obtaining a positive result also in learning what is the true temperature in the center of the sun and what thermonuclear reactions "define the tone" in this gigantic star boiler, feeding our entire planet with energy.

As early as the beginning of the 1960's the existence of two types of neutrinos, which received the name of electron and muon (ν_e and ν_μ) was proven with the aid of accelerators. The first, about which we spoke above, always "works" in a pair with an electron (for example, in the decay of λ-hyperon $\lambda \to p + e^- + \bar{\nu}_e$; the second, in a pair with a muon, for example, in the decay of a π-meson

$$\pi^+ \to \mu^+ + \nu_\mu$$

Such a "pairing" is explained by the law of the preservation of special lepton charges: $L_e = +1$ for electron e^- and the electron neutrino ν_e (an correspondingly, $L_e = -1$ for e^+ and $\bar{\nu}_e$); $L_\mu = +1$ for the negative muon μ^- and the muon neutrino ν_μ (but $L_\mu = -1$ for μ^+ and $\bar{\nu}_\mu$). Therefore, in the disintegration $\mu^- \to e^- + \bar{\nu}_e + \nu_\mu$, neutrinos of both types are "obliged" to take part.

The difference in principle between the two lepton charges by nature, and also their very difference from zero leads to the fact that, for example, the reaction $\bar{\nu}_\mu + n \to p + e^-$ simply does not have the "right to existence" (this very experiment was proof of the variety of ν_e and ν_μ), just as the reaction $\nu_\mu + p \to \mu^+ + n$ (the latter would designate the identity of the particle ν_μ with its antiparticle $\bar{\nu}_\mu$). /59

The chief physical characteristic of both neutrinos is the so-called spirality, reflecting the fact that the direction of their angular momentum (polarization) is always opposite the vector of impulse (the direction of movement). This property is sometimes expressed in short form by the term "left spirality."

From this follows automatically, in particular, the surprising phenomenon of the non-preservation of parity, discovered in 1957: thus, in the decay of cosmic μ-mesons the electrons fly out primarily downward, as if "remembering" the primary direction of movement of the already stopped muon, in seeming contradiction to the obvious principle of isotropy of space.

From the point of view of the physics of elementary particles, an experiment with muon cosmic neutrinos of very high energy (more than 10 GeV) seems very attractive. The interactions of cosmic rays with atomic nuclei of the upper layers of the atmosphere serve as a source of such particles with which muons, pions, and kaons with various sign charges (and also neutral kaons) are born.

The neutrinos born during the decay of the enumerated particles can again interact with oncoming atomic nuclei, although with an insignificantly small cross-section. As experiments in accelerators showed, neutrinos and antineutrinos with energy of 10 GeV yield interactions which are basically inelastic, according to the schemes

$$\begin{aligned} \nu_\mu + N &\rightarrow \mu^- + N' + k\pi, \\ \bar{\nu}_\mu + N &\rightarrow \mu^+ + N' + l\pi. \end{aligned}$$

(N, N' are nucleons, $\mu^\pm$ are muons, π are pions). The cross-sections of interactions of the neutrinos with nuclons are

equal with this to $0.8 \cdot 10^{-37}$ cm^2, but they still continue /60
to increase proportionally to the energy. For antineutrinos the cross-sections can turn out to be only smaller (2-3 times), as experiments at low energies in accelerators show, and also model theoretical images of the nuclon as the totality of special "subparticles" which are strongly connected with one another - quarks with an undefined mixture of their antiparticles - antiquarks.

In order to represent clearly the vanishingly small size of a cross-section of 10^{-37} cm^2, we will note that in a column of earth rocks with a cross-section of 1 cm^2, which passes through the whole earth's sphere through the diameter it will contain something like 10^{33} nucleons. This means that in the stream of neutrinos only one-hundredth of a percentage of the particles undergoes interaction with the planet earth! But this very sad circumstance practically permits the exclusion of phonons connected with the direct detection of muons of cosmic radiation. For this purpose, it is necessary, in the first place, to set up the detecting apparatus deep under the earth, and in the second place, to produce only muons which pass at a sufficiently large angle to the vertical.

The high energy, and that means also the large range ($\gg$ 200 m of matter) of the bred muons, is a circumstance which strongly simplifies the experiment, and, therefore, the surrounding rock automatically becomes part of the experimental apparatus. In considering all these circumstances, the expected rate of calculation of secondary muons is from 0.05 to 0.1 for each square meter of apparatus per year in calculation for a working angular aperture of 1 steradian.

In the 1960s two groups of experimenters at the same time ventured to go on a "hunt" for cosmic neutrinos of high energy.

One of them, an Anglo-Indian group (A. Wolfendale, J. Menon, and others) over the course of 5 years (1965-1969) was based at the gold-bearing mine of the Kolar Gold Fields in Southern India. Under a layer of soil 750 kg/cm^2 thick ($\sim$7.5 km of water equivalent), this group placed apparatus in three different variations. One of them (Fig. 19) includes plastic scintillation counters and long thin gas-discharge (neon) tubes, which allow the marking of the trajectory of the passing of a muon by flashes. In one of the variations, thick (40 cm) filters of magnetized iron were also added, allowing a determination not only of the sign of the charge, but also the impulses of the muons. /61

Another group, (F. Reines with assistants) worked over a period of 8 years in depths of up to 900 kg/cm^2 in a mine near Johannesburg (South Africa). It used more than 50 huge liquid

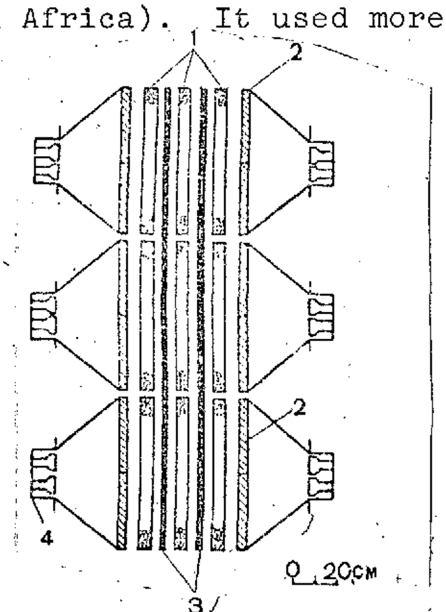

Fig. 19. One of three telescopes for the registration of processes of the type $\nu_\mu + N \to \mu^- + N' + n\pi$ in the mine of the Kolar Gold Fields (India): 1--neon (gas-charged) tubes; 2--scintillation counters; 3--lead absorbers (thickness of 2.5 cm); 4--photoelectron multipliers.

scintillators (dimensions of each - 5.5 m x 0.56 m x 0.13 m) laid out in two parallel rows along the wall of a horizontal drift.

At the International Neutrino Conference in Budapest in the summer of 1972 in the report of Wolfendale et. al. an analysis was given of the results obtained on both devices, agreeing with one another within the limits of statistical errors. But these results were not too definite and have the character of indications or even hints.

First result. The possibility of weak interaction passing through an intermediate stage of transformation and decay of a heavy vector W-meson was not excluded, but under the condition that its mass consists of not less than 3 GeV (in energy units).

Second result. Regardless of the existence of a W-meson, the presence of some factor leading to the saturation of a complete cross-section of weak interaction at energies of tens of GeV may be suspected, although the hypothesis on linear increase in the cross-section with energy also passes with a 5% probability.

A Word About Prospects

The science of cosmic rays was born at the beginning of /62 the 20th century as a branch of geophysics deriving from the problem of explaining the heightened ionization of atmospheric air. As early as the 1920s it began to attract the attention of astrophysicists in connection with the problem of extra-terrestrial sources of particles of superhigh energies, which has by no means been solved even to this day. In the 1930s lively interest was aroused in cosmic rays as a source of new elementary particles and the processes of their transformations. In the 1950s there began an epoch of waning interest in cosmic rays along the line of the physics of elementary particles -

accelerators had already turned out to be a very powerful, gigantically growing competitor for them. Somewhat later a certain "cooling" began also toward the cosmophysical branch of the physics of cosmic rays, if its interests are taken narrowly - only as the physics of charged particles of superhigh energies. A proper question on the part of the reader will be -what next?

It is impossible not to take into consideration the fact that the energies accessible by accelerator technology are increasing constantly, and the ideal of building accelerators with oncoming proton beams with equivalent energy of about 10^{15} eV by 1980 has already become completely real. And these are already almost the maximal energies of the particles directly discovered and measured by the apparatus of cosmic specialists. But actually the situation is by no means so tragically hopeless for the "cosmic-nuclear specialists." Both for complex nuclei and especially for nonstable particles (primarily pions), the possibilities of acceleration and accumulation of streams of particles is by no means so great as for protons and even electrons. Therefore, in a study of cosmic rays with their huge "assortment" of particles in width, it is necessary to know how, first of all, to select rational objects of investigation, their tasks, and constantly to work on the development of apparatus and methods, directed first of all to energies which exceed accelerator capabilities by about 2 to 3 times.

The cosmophysical trend of investigations is a different matter. All the processes connected with acceleration of various particles in stars (beginning with the star nearest to us - the sun) are of great interest for an understanding of those physical conditions which prevail in their shells. Especially important are data on fast-moving, nonstationary processes and the more so if it concerns a wide range of /63 energies of both the particles themselves and the radiation produced by them. As we became convinced by the example of solar flares, in a number of cases it is important to penetrate into the field, not so much of very high, as of comparatively low energies that are typical for the physical "situation" in the object studied, and first of all, its temperature.

And in the future, as now, a detailed study of the properties of cosmic rays and especially of their nonhomogeneity in time and space can yield much for an explanation of the characteristics of the interplanetary and, particularly, of the interstellar medium and, especially, of cosmic plasma with magnetic fields "frozen" in it. But in this case also the information yielded by fluxes of charged particles coming to the earth needs substantial specification and additions. We are speaking particularly about the consideration of the "breathing" of the earth's magnetosphere and the fiery "breathing" of the sun - the solar wind--which can and must be studied by methods independent of cosmic rays.

One must not forget also the direct methods of study of the history of cosmic rays which are inscribed by nature itself by special signs - the so-called cosmogenic isotopes of various chemical elements in minerals and rocks of meteorites and the moon, which were irradiated for many years by cosmic radiation without hindrance.

Thus real success may be ensured only by the joint efforts of physicists, astrophysicists, geochemists, and cosmochemists, and, finally, engineers, who are creating ever newer technical methods for detecting particles and radiation, for delivering the detection apparatus far beyond the bounds of the earth and, finally, for transmission of the corresponding scientific information "home."